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An evaluation of the primary factors which influence proportionality failure

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's Thesis of

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AN EVALUATION OF THE PRIMARY FACTORS WHICH INFLUENCE PROPORTIONALITY FAILURE

by

Daniel M. Levine

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
School of Printing in the College of Graphic Arts and Photography
of the Rochester Institute of Technology

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In the beginning there were two friends and myself. Now there are newer friends and potentials which did not exist before. To Dr. Robert Hacker and Dr. Mark Guldin I express my gratitude for providing me with the tools to realize those potentials. To Dr. Julius Silver I extend my profound thanks for having the faith in my ability to use those tools. And, to Irv Pobboravsky, whose help and advice was critical to my studies, may your life be blessed with good spirits. Lastly, to Daniel, Deborah, and Janet, thank you for making it all so much fun.

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An Abstract

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ABSTRACT

If practical colorants could be found to meet theoretical requirements then there would be no need for color correction in multi-color printing. Color correction is necessary because the available yellow, magenta, and cyan inks absorb and transmit in all parts of the visible spectrum.

It is possible to measure how much these colorants deviate from the ideal with the use of a reflection densitometer. The red, green, and blue filter positions on a densitometer will read the cyan, magenta, and yellow densities, respectively. From these densities the amount of color correction necessary to compensate for the inks deficiencies is expressed in terms of percent masking. This is usually computed by the formula:

$$\text{percent mask} = \frac{\text{highest unwanted density}}{\text{wanted density}}$$

The percent mask is often computed from the densities found when measuring a solid area of a particular colorant. The ratio of unwanted densities to wanted densities is often assumed to remain constant for solids and tints. This is the proportionality rule and is assumed to hold true in what are known as the masking equations (which are the basis for photographic masking for color correction.) The problem is

that when a graduated scale of a single color is printed from a light tint to a solid, the proportions of the wanted and unwanted densities do not remain the same for varying tint values and solids. This is known as proportionality failure. This paper deals with the statistical evaluation of the three factors (and the interactions between them) which have been suspected of being the primary causes of this phenomenon. The three factors being tested are solid ink density (ink film thickness), type of paper, and half-tone screen ruling. The results indicated that screen ruling was the most important factor for all colors with solid ink density being the next in importance. But the type of paper used was not found to influence proportionality failure, except with magenta ink. This, along with the fact that there was very little proportionality failure in yellow ink, may indicate a certain degree of confusion between proportionality failure and the influence of various factors (including paper) on the 'purity' of a color.

It was shown in this experiment that the optimum printing levels which produce the least amount of proportionality failure were at the lowest solid ink density practical, the finest screen ruling, and on uncoated paper (yellow notwithstanding since it displayed comparatively no proportionality failure.) The implications of these results indicate that certain modifications in color correction

methods may be necessary if printing conditions deviate widely from these optimum levels.

Abstract approved:

Julius L. Silver, thesis adviser

Assoc. Prof,-Printing, title and department

July 9, 1976, date

CHAPTER I

INTRODUCTION

Proportionality Failure

In order to evaluate color correction methods for multi-color printing it is not only necessary to understand the characteristics of subtractive color but to also investigate inherent limitations in the materials and processes being used. The primary concern of this paper deals with the limitations imposed on color printing by the phenomenon known as proportionality failure.

The proportionality rule states that for all levels of colorant amount the unwanted density is proportional to the wanted density as measured with a reflection densitometer. Proportionality failure in multi-color printing refers to the inability for this rule to hold; i.e., unwanted density is not proportional to colorant amount. This failure is important because it relates to color reproduction equations which dictate certain photographic and scanning color correction requirements for multi-color printing. Color reproduction equations compute the colorant amounts needed in the reproduction to match the original. These equations (which shall be discussed in the Literature Review) do not address themselves to two important points:

1. Color reproduction equations do not take into account colors that are not reproducible (outside the ink color gamut) where some compromise is necessary.
2. Except for empirical equations, color equations either assume the proportionality rule holds, or don't recognize that proportionality failure may have an influence in predicting proper colorant amounts. Even the empirical equations, which take both proportionality and additivity failure into account, are not accurate for colors that are outside of the data-reference-base which determine the coefficients for the equations.

Since these reproduction equations influence color correction methods, the implication is that the affect of proportionality failure may dictate a need to change color correction requirements for multi-color printing. The easiest way to investigate proportionality failure is to analyze a single color printed from a light tint (10% printing dot) to a solid patch. When a scale of magenta is printed using a given screen ruling the ratio between the green and blue filter density readings (highest unwanted density vs. highest density) is not the same in the light tints, middle tones, and solids. This means that if one were to plot a curve of the wanted density (green filter density in the above example) versus the unwanted density (red or blue filter densities) the curve would not be a straight line as the proportionality rule would dictate (see Figure 1).

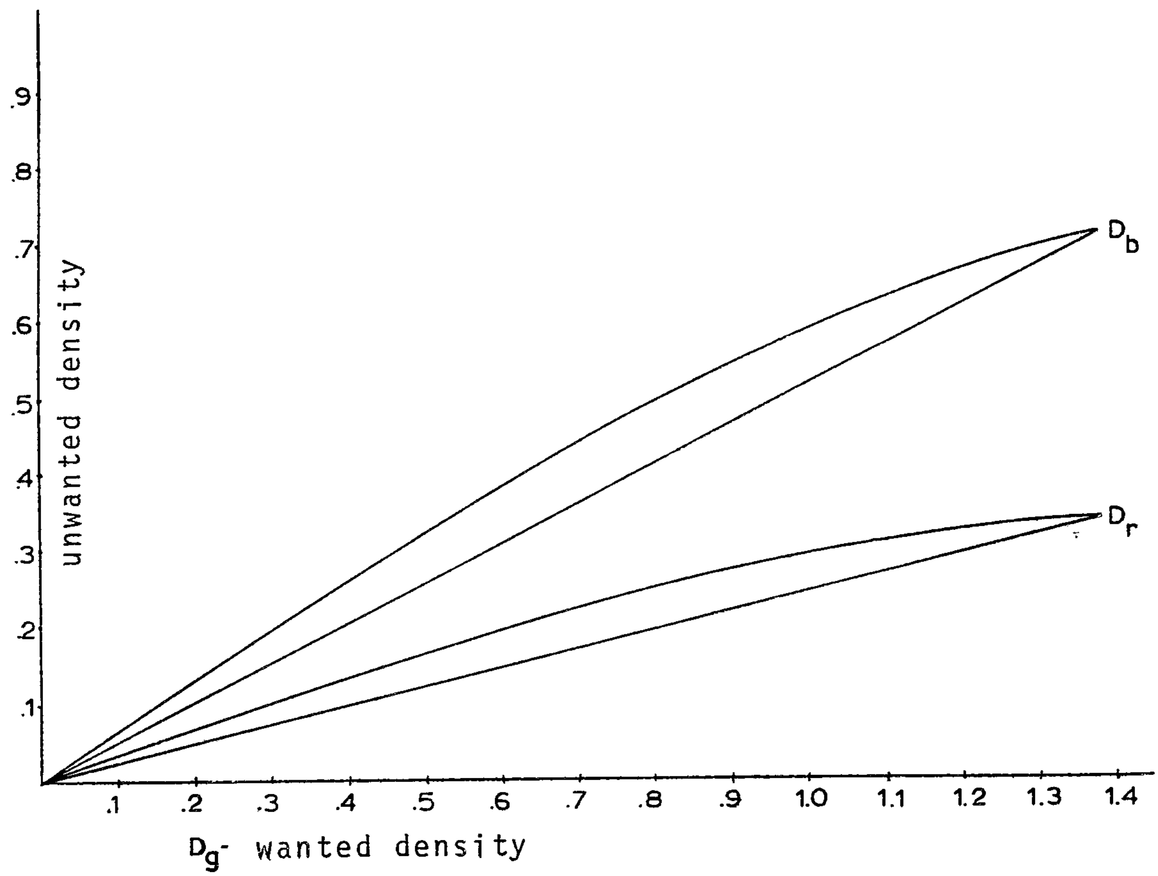

Figure 1. Proportionality curve for magenta ink.

Causes of Proportionality Failure

First Surface Reflection

First surface reflection is defined as the amount of light which is reflected off of the top layer of ink without having penetrated the ink film, and limits the maximum density of reflection copy. The effect of first surface reflection on the printed density can be calculated by converting the density into reflectance, adding the surface reflectance, and converting back to density. A small correction factor is added in order to bring the reference white back to zero depending on the substrate that is being used. The formula is: $D' = -\log(10^{-D}+S) + \log(1+S)$ where S is the surface reflection, D' and D are densities with and without surface reflectance and 10^{-D} is equal to the reflectance corresponding to density D. The effect of a 4% surface reflectance on proportionality failure calculated from the above equation is shown in Figure 2.[1] This curve is derived from measurements taken on a magenta scale. In the upper curve the ratio of the two densities has been plotted against the density of the green filter.

It is important to note that the effect is small except near the maximum density. With no proportionality failure one would expect the lower curves in Figure 2 to be straight diagonal lines while the curves of the ratios would normally be straight horizontal lines. The experimental design for this thesis will not include the statistical analysis of this factor. Since first surface reflection limits maximum density its effects will be 'zeroed-out' by using a solid patch as a reference point to determine the amount of proportionality failure occurring with each sample.

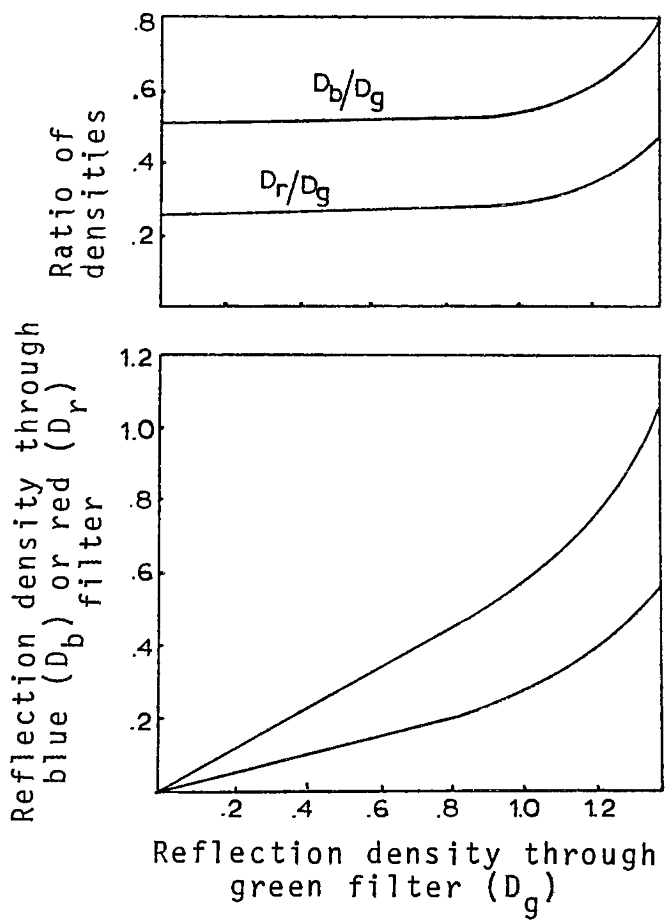

Figure 2. Affect of 4% surface reflection on proportionality failure.

Multiple Internal Reflections

A large portion of the light which passes through an ink film does not emerge directly, but is scattered by the various components of the ink. Each time the light is scattered or reflected back to the paper, more light is absorbed which increases the density. This increase in density, however, is not proportional to the amount of light scattering material in the ink film.

Halftone Pattern

Apparently this is the most important factor which influences proportionality failure. With finer screens the amount of failure is less than with coarse screens. Light tints appear dirtier than shadows using the same screen ruling. This might mean that color correction requirements may differ not only for what screen ruling is used but also for light tints versus shadows.

Paper and Color

Both the type of paper used and the color of ink seem to influence proportionality failure.[2] There is to date, however, no qualitative or quantitative evidence to support these assumptions. This will be one of the objectives of this study.

Additivity Failure

The additivity rule states that the integral density of overprinted colors is equal to the sum of the individual colorant densities measured separately. When a set of four process inks are overprinted the resultant density measured through color analyzing filters on a reflection densitometer is usually considerably less than the sum of the densities of the individual inks. This is known as additivity failure and also has a bearing on color reproduction equations and their accuracy.

The following are the main causes of additivity failure: first surface reflection, multiple internal reflections, halftone pattern, light scatter in paper, ink trapping, opacity, back-transfer effects, and spectral characteristics. The first four causes are also associated with proportionality failure and have been discussed in the previous section.

Ink Trapping

Ink trapping is defined as the ability of one ink film to accept or hold an overprinted ink film. The amount of ink which is transferred to a previously inked area is different than the amount of ink transferred to clean paper. With the variability of ink film thickness and the overlapping of halftone dots, the uniformity of the deposit will also fluctuate, affecting the additivity of the densities.

Opacity

The opacity of an ink film refers to the scattering of light caused by the differences in the refractive index between the pigment and vehicle. An opaque ink will reflect a certain amount of light before it penetrates the underlying substrate. If less light reaches underprinted ink film layers, even less light will pass through the opaque ink again; meaning the underlying ink will not appreciably contribute to the total density.

Back Transfer

If an ink film layer is still wet when the next color is applied, some of it could be transferred from the paper to the second ink, changing the color and the density.

Spectral Characteristics

With two or more overprinted inks the additivity of densities depends on the spectral characteristics of both the inks and the measuring instrument with its set of color analyzing filters. It is often possible to compensate for this with the use of broad band filters. This compensation, however, is usually correcting other deficiencies and in certain cases over compensation is possible, creating super additivity. Super additivity occurs when two inks are overprinted and the second ink increases the gloss of the first. If the instrument used to measure the density is not influenced by gloss, this will cause the integral density to be more than the sum of the individual densities.

Ink Emulsification

Although this is not generally considered, ink emulsification might play an important part in both additivity failure and proportionality failure. It has been found that at the thinnest ink film levels acceptable for printing the degree of ink emulsification will influence the solid ink density.[3] This factor could be investigated in a separate experiment, but it shall not be done here due to the extensive nature of testing that would be involved.

AREA OF INVESTIGATION

Possible Areas

There are many variables associated with proportionality failure whose significance and effects are not well understood. Some of these variables have already been mentioned. Also of importance are the variables of printing such as fountain solutions, blankets, ink tack, press speeds, temperature, humidity, etc.

While these printing variables are of great significance they only relate to proportionality failure indirectly. An area that is more basic and perhaps more worthwhile for future investigations deals with the variables mentioned earlier: type of paper, ink color, halftone screen ruling, and multiple internal reflections. These variables are generally considered to be the primary factors which directly influence proportionality failure. Printing variables are a secondary concern and shall be controlled as closely as possible. At this point two questions come to mind:

1. How significant are each of these variables in their influence on proportionality failure?

2. How are these variables interacting with one another?

To date there has been no serious attempt to statistically determine the significance of these variables and their interactions with one another. Furthermore, the subsequent implications of the effect of proportionality failure to photographic color correction methods has never been considered important when in fact it may be under certain conditions.

In any case it seems that an attempt must be made to resolve these questions and implications. Therefore, the variables associated with proportionality failure will be dealt with in the following manner:

Multiple Internal Reflections - This would be a problem if it were dealt with as it is usually presented, which is in a long and complicated formula. This variable will be associated with ink film thickness (thicker ink films will cause more internal reflections) which, unfortunately, has its own complicated problems of measurement. Since it is inaccurate to use the term 'ink film thickness' (there is no actual film which rests on top of the substrate) and since there are numerous problems associated with any available technique to determine the amount of ink deposited on the paper, solid ink density will be the index for relative 'ink film thickness'. The solid ink densities used will be representative of what is being used in the industry for a particular color on the kind of paper used for this experiment.[4] Since in the experiment each sample will be replicated twice, the acceptability limits of variability for the density of each pair of samples will be $\pm$ .03. It shall be assumed that if equal densities are obtained on a particular kind of paper with a particular color ink (printed on the same side of the sheet) then there will be no appreciable difference in the amount of ink deposited on the paper (same 'ink film thickness').

Paper, Ink Color and Halftone Screen Ruling - Only one particular brand of cyan, magenta, and yellow will be used in this experiment. The screen rulings used will be 65, 100, and 150 lines per inch which are, again, representative of industrial applications. The problem, however, will be obtaining consistent paper samples. Paper samples will be checked for consistency by determining their surface efficiency properties.[5] Any other inconsistencies in the paper will be attributed to experimental error.

Combination Effects - Since all of the above factors could be interacting with one another, the experiment will be designed to test for all possible interactions and their significance.

Proposal and Hypothesis

It is proposed to determine the statistical significance of the primary variables which influence proportionality failure. The variables or factors under consideration will be ink film thickness, ink color, type of paper, and halftone screen ruling. It is hypothesized that there is no significant difference between any of the above variables in their influence on proportionality failure. This statement has a statistical significance and shall be explained in the methodology. Since this hypothesis is expected to be invalid an alternate hypothesis shall also be proposed which states that optimum printing levels needed to produce the least amount of proportionality failure with single color images include printing with the finest screen ruling possible and the thinnest 'ink film' that is practical on paper with high surface efficiency properties. This proposed alternate hypothesis indicates possible optimum multicolor printing conditions that are not normally supposed. Furthermore, there is a subsequent implication that proportionality failure may have a significant role in masking requirements (under certain conditions) that are not taken into account. Images printed with a coarse halftone screen may require stronger masking than the same image printed with a very fine screen. It is also possible that masking curves might need to be modified for certain inks to allow for greater deviation in light tint or highlight areas.

Variables and Effects

Inferences will be made into the relationship between proportionality failure and masking requirements for color separation. If the influence of each variable is known it might be possible to assume that changes may be required in the masking and color correction requirements for some of the printing conditions studied in the experiment.

FOOTNOTES FOR CHAPTER I

[1] John A. C. Yule, Principles of Color Reproduction, (J. Wiley and Sons, 1967), p. 209.

[2] Ibid., p. 210.

[3] Charles E. Martin, "The Principles of Screenless Lithography," Master's Thesis, R.I.T., 1975.

[4] Gary Field, "The 1970-71 GATF Color Survey," GATF, 1971.

[5] Frank Preucil, "A New Method of Rating the Efficiency of Paper for Color Reproductions," GATF, Report of Progress, Number 60.

CHAPTER II

LITERATURE REVIEW AND THEORETICAL BASIS

COLOR REPRODUCTION EQUATIONS

Masking Equations

In order to estimate the relationship between the amount of each ink printed and the resultant color, three equations are considered. All of these equations have certain limited applications. The first set of equations apply to continuous tone rather than halftone images, and are the basis for photographic masking:

$$C_R = a_{11} \left(D_R + \frac{a_{12}}{a_{11}} D_G + \frac{a_{13}}{a_{11}} D_B\right)$$

$$M_G = a_{22} \left(\frac{a_{21}}{a_{22}} D_R + D_G + \frac{a_{23}}{a_{22}} D_B\right)$$

$$Y_B = a_{33} \left(\frac{a_{31}}{a_{33}} D_R + \frac{a_{32}}{a_{33}} D_G + D_B\right)$$

C_R, M_G, and Y_B are wanted densities and represent the amount of colorant needed. The first letter identifies the color of the ink (cyan, magenta, and yellow) and the subscript signifies the filter used to measure the ink (red, green, or blue). D_R, D_G, and D_B are the integral densities of the superimposed inks as measured through the red, green, and blue filters, respectively. The coefficients inside the brackets relate to the percent masks needed for each ink where;

$$\text{Percent mask} = 100 \times \frac{\text{density range of the mask}}{\text{density range of the original}}$$

The deviation of these equations is not the primary concern here. How the equations are used and the assumptions that are made, however, are important. Firstly, these equations assume that with the colorants and processes used the proportionality rule holds. In other words these equations are supposed to be able to predict the colorant amounts needed, given the red, green, and blue densities of the color being reproduced, which they don't. Secondly, these equations also assume that the additivity rule holds, which also adds to their inaccuracy. Thirdly, these equations can be used to calculate mask percentages, which means that if their predictive capabilities are inaccurate in determining proper colorant amount then the predicted mask percentages may also be inaccurate.

Neugebauer Equations

The Neugebauer equations are based on the percent printing dot areas of the different colors in the halftone pattern. In order to understand both the deviation and application of these equations it is necessary to imagine an enlarged triad of the three overlapping colors of halftone dots. In this triad there are eight colors:

- cyan, magenta, yellow -- single colors

- magenta + yellow, cyan + yellow, cyan + magenta -- two-color combinations

- cyan + magenta + yellow -- three-color combination

- white paper

The degree of overlap of these dots will vary due to the angling of the screen. Demichel worked out the relative fractional areas covered by each of these eight colors averaged over a large area (Yule, J.A.C., Principles of Color Reproduction, p. 261):

	Average fractional area covered by:
$f_1 = (1-C)(1-M)(1-Y)$	white paper
$f_2 = C(1-M)(1-Y)$	cyan
$f_3 = M(1-C)(1-Y)$	magenta
$f_4 = Y(1-C)(1-M)$	yellow
$f_5 = MY(1-C)$	red (magenta + yellow)
$f_6 = CY(1-M)$	green (cyan + yellow)
$f_7 = CM(1-Y)$	blue (cyan + magenta)
$f_8 = CMY$	three-color black

The final reflectance (red, green, or blue) of a particular color will be the sum of the corresponding reflectance of each of these eight colors multiplied by the fractional area each color occupies. The Neugebauer equations are then represented by the following:

$$R = f_1R_1 + f_2R_2 + f_3R_3 + f_4R_4 + f_5R_5 + f_6R_6 + f_7R_7 + f_8R_8$$

$$G = f_1G_1 + f_2G_2 + f_3G_3 + f_4G_4 + f_5G_5 + f_6G_6 + f_7G_7 + f_8G_8$$

$$B = f_1B_1 + f_2B_2 + f_3B_3 + f_4B_4 + f_5B_5 + f_6B_6 + f_7B_7 + f_8B_8$$

where R, G, and B are the red, green, and blue reflectances of the final color. To reproduce a given color, the red, green, and blue reflectance of that color along with the red, green, and blue reflectance of the eight 'Neugebauer primaries' will be known. These equations can then be solved indirectly to determine the percent printing dots for cyan, magenta, and yellow.

Even though equations such as these are somewhat removed from practical situations it must be pointed out that the efficiency of color correction methods depends on how accurately these equations can predict actual results. How well do the Neugebauer and masking equations predict? A scale of cyan incremented from white (0% printing dot) to solid (100% printing dot) is used as an example. Since the red filter measures the wanted density and the green filter measures the highest unwanted density, only these two filter readings will be considered.

Using the masking equations it is assumed that these two densities are proportional throughout the tonal scale, in which case a curve of the green filter density versus the red filter density would be a straight line. Solving the Neugebauer equations yields a curve which indicates higher green filter densities. So the masking equations indicate that cyan tints would have purer tints than what the Neugebauer equations predict. In actuality the results fall in between the two curves (see Figure 3).[6]

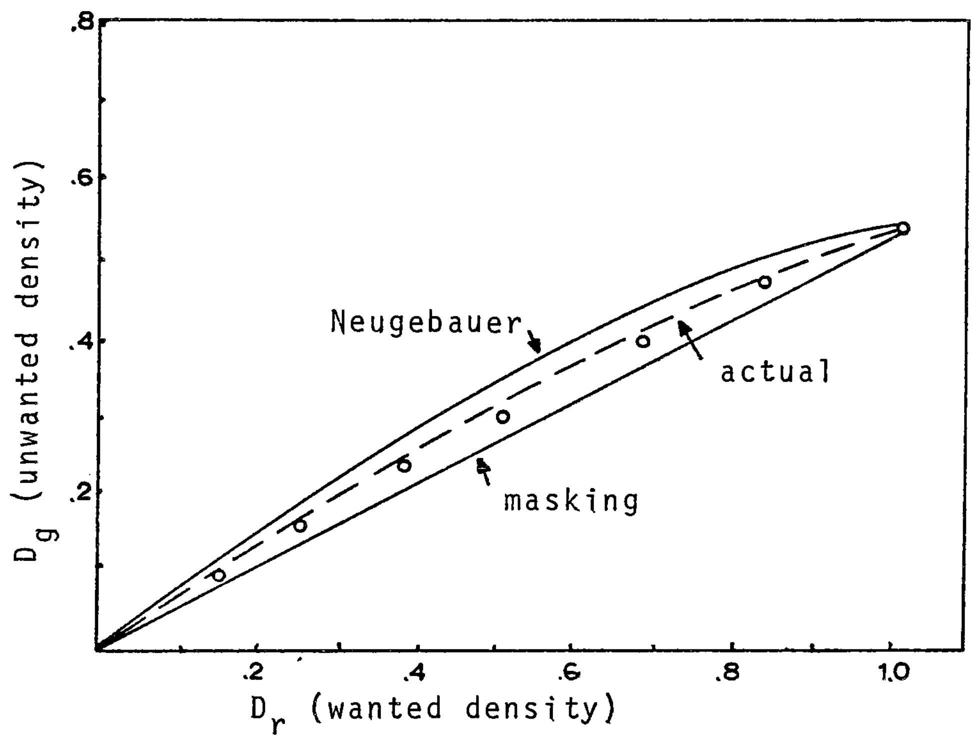

Figure 3. Neugebauer and masking equations plotted with the actual case.

Empirical Equations

As has been stated before, both the proportionality rule and additivity rule do not hold for printing halftone images on paper. The actual ratios of wanted and unwanted densities for a given color is not linear (see Figure 1), meaning the relationship is non linear and is more accurately described by the general equation

$$y = k_1 x + k_2 x^2 \ldots$$

Or more specifically;

$$c_G = k_1 C_R + k_2 C_R 2$$

where c_G is the unwanted green filter density of the cyan ink and C_R is the wanted red filter density. Since the additivity rule is also invalid then the integral density of overprinted inks is not equal to the sum of the densities of the individual inks:

$$D_G \neq \underbrace{[k_1 C_R + k_2 C_R^2]}_{\text{green density of cyan}} + \underbrace{[k_3 M_G]}_{\text{green density of magenta}}$$

It would be possible to account for this failure by adding a cross-product term but the additivity and proportionality of different ink sets is not the same.

Instead of deriving a theoretical set of equations to take both proportionality and additivity failure into account, a set of equations could be derived empirically. In this case a large sample of colors is printed with a particular set of inks with all possible combinations. The integral densities (D_R, D_G, D_B) and the single color amounts (C_R, M_G, Y_B) for each color are determined and a 9-term mathematical model is selected and the coefficients for the model are found for each colorant using the sum-of-least-squares method:

$$C_R = a_{11}D_R + a_{12}D_G + a_{13}D_B + a_{14}D_R^2 + a_{15}D_G^2 + a_{16}D_B^2 + a_{17}D_RD_G + a_{18}D_RD_B + a_{19}D_BD_G$$

$$M_G = a_{21}D_R + a_{22}D_G + a_{23}D_B + a_{24}D_R^2 + a_{25}D_G^2 + a_{26}D_B^2 + a_{27}D_RD_G + a_{28}D_RD_B + a_{29}D_BD_G$$

$$Y_B = a_{31}D_R + a_{32}D_G + a_{33}D_B + a_{34}D_R^2 + a_{35}D_G^2 + a_{36}D_B^2 + a_{37}D_RD_G + a_{38}D_RD_B + a_{39}D_BD_G$$

where D_R, D_G, D_B are integral densities and C_R, M_G, Y_B are the amounts of cyan, magenta, and yellow. From the above equations are three sets of nine coefficients. Once the coefficients are found from the data the equations can be used to reproduce any set of densities based on a given 'standard'. This 'standard' or data base can be a set of neutrals (in which case $D_R = D_G = D_B$) or saturated colors. While the empirical equations always predict with greater accuracy than both the Neugebauer and masking equations, they cannot be expected to predict quite as accurately when reproducing colors not based on the standard data base (which was used to derive the coefficients).

Printing Errors

Optimum Reproduction

> Graphic arts color reproductions whether by gravure, letterpress or offset, are essentially the same in being multiple layers of colored ink on paper, or other support, and it is only the optical properties of the mixed layers which actually transfer and remain on the paper that we may compare to the original. The printing plates, or the negatives or positives which produced them, are in no sense a measurable criterion or forecast of the finished reproduction unless we have complete knowledge of the transferred ink layers. No intelligent corrections can possibly be applied, or should we expect facsimile reproduction unless we understand and keep control of all printing error variables.[7]

A problem which has arisen over a period of time is whether photographic or scanning masking corrections should be different for letterpress, offset, or gravure. Letterpress and offset print variable areas of dots of approximately equal ink distribution. Gravure often achieves tonal differences not only with variable dot size but with varying distribution of ink (variable cell depth). It is of significant importance to ask if these two conditions are equivalent. Figure 4 shows two Maxwell triangles which are the previous results of Frank Preucil.[8] These diagrams are not necessarily the same for all sets of inks but the conclusions are the same; variable ink film has a significant effect on proportionality failure. This being the case, it is quite possible to reduce the adverse affects of proportionality failure in offset printing by changing the ink film (or solid ink density) being used.

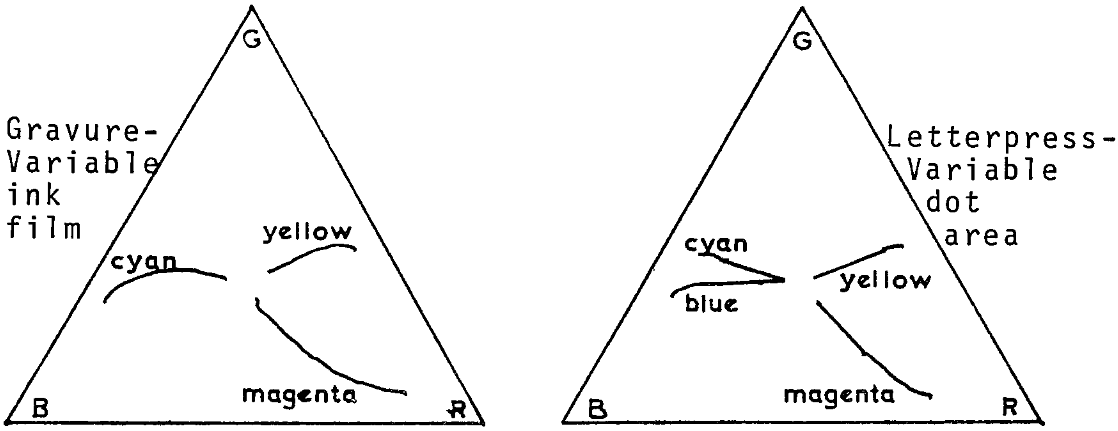

Figure 4. Hue error shifts - Variable ink film and dot area.

Gravure printing often has the advantage of varying cell depth to achieve variable ink film thickness. It was also found by Preucil that as the paper area increased while keeping the cell depth constant, the hue error, or proportionality failure, changed drastically. The implication here is that changes in dot area may change the resultant proportionality failure (particularly in light tints) enough to warrant changes in color correction requirements.

Figures 5 and 6 show the masking curves required to correct for the hue changes seen in Preucil's Maxwell triangles for cyan ink. Figure 5 is a concave mask needed for gravure (variable ink film) while Figure 6 is a convex masking curve which satisfies the correction requirements in letterpress and certain offset processes. A linear mask of the proper strength for the solid areas would overcorrect the

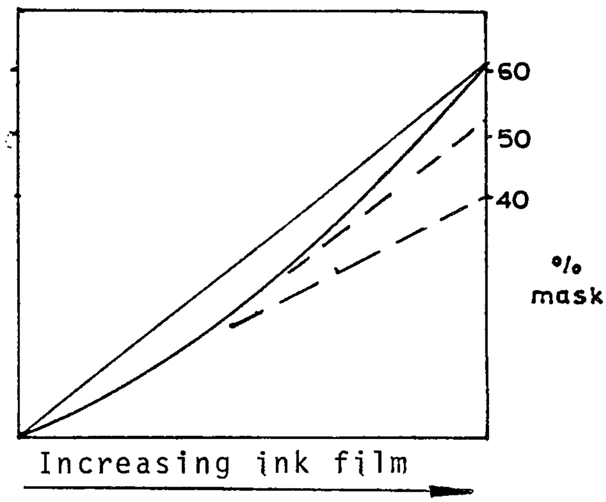

Figure 5. Concave mask curve for variable ink film.

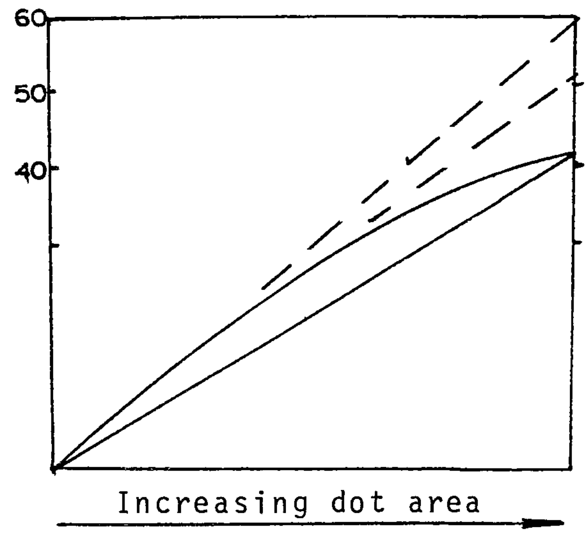

Figure 6. Convex mask curve for letterpress and offset.

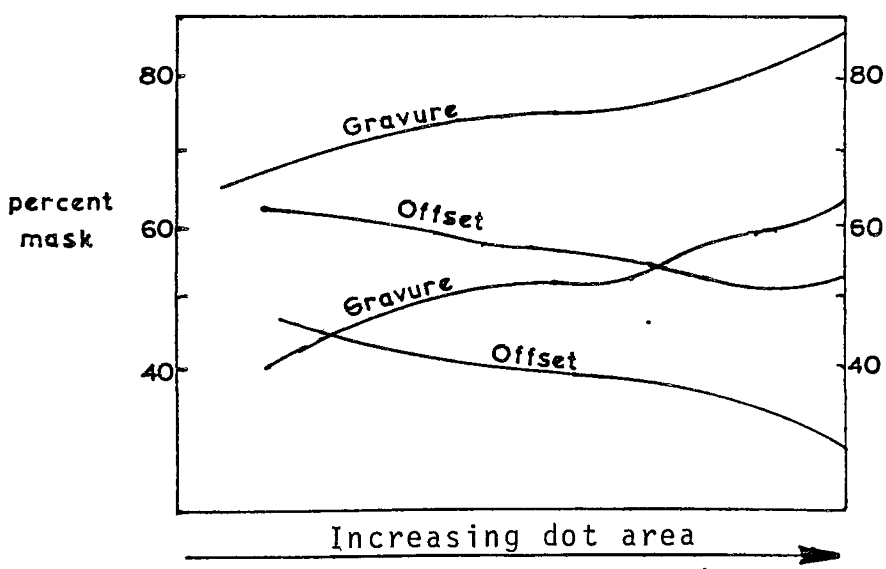

Figure 7. Opposite correction shifts (gravure and offset).

midtones on the gravure print by 25%. The same mask would undercorrect the midtones of the letterpress print by 25 - 30%.[9] The solid straight lines in Figures 5 and 6 represent the linear mask of the proper strength. The dotted lines represent the proper strength mask for highlight and midtone areas. Since percent mask is a function of the slope of the lines, the difference in slopes is what dictates how much over - or under - correction is taking place in the highlights or midtones. Figure 7 shows the opposite correction shifts that are characteristic of gravure and offset.[10]

It now seems pertinent to obtain a better understanding of the role of each variable affecting proportionality failure and the interactions which may be taking place. At the present time the best and most efficient method for determining the effects and interactions of a number of variables is to run a statistical factorial experiment with the results being analyzed by the Analysis of Variance (ANOVA) technique. This is described in the Methodology which follows.

FOOTNOTES FOR CHAPTER II

[6] R. Colt and John A. C. Yule, "Colorimetric Investigations in Multicolor Printing," _TAGA Proceedings_, 1951, p. 78.

[7] Frank Preucil, "Color Hue and Ink Transfer - Their Relation to Perfect Reproduction," _TAGA Proceedings_, 1953, p. 105.

[8] _Ibid._, p. 106. [9] _Ibid._, p. 107.

[10] F. R. Clapper and John A. C. Yule, "Reproduction of Color with Halftone Images," _TAGA Proceedings_, 1955, p. 8.

CHAPTER III

METHODOLOGY AND RESULTS

Factorial Experiments

In the classical controlled experiment one factor is kept constant while another is varied. Another similar experiment would be necessary to test other variables, or the same variables at different levels. A group of controlled experiments suffers from numerous faults:

1. Each factor is tested at only one controlled level of each of the other factors.

2. Experimental error could be quite significant unless all experimentation were done under exactly the same conditions.

3. It is actually very rare that we are able to control the factors which are not being tested.

Factorial experiments, on the other hand, study the effects of several factors at the same time. In the case of this research paper four factors will be tested at three levels each. Mathematically this can be described as a 3^4 factorial requiring a minimum of 81 samples (with no replication) to obtain a statistical basis for comparison. This type of experiment has the following advantages over the classical controlled approach:

1. It is possible to test the effect of each factor at the specified levels of the other factors.

2. Consequently, it is possible to test for interactions between factors at two or more combined levels.

3. Each statistical judgement is based on all of the data taken and not only a few observations. This means there is a greater sensitivity in finding the significant factors.

Treatments

A treatment is a single run of a factorial experiment using a specific combination of the levels and factors being tested. In order to simplify the analysis of the factorial experiment the following method (see Tables 1 and 2) of designating the different treatments will be used:

TABLE 1

FACTORS AND LEVELS FOR FACTORIAL EXPERIMENT

Factor

		Color	Paper	Screen Ruling
Level	Low	Yellow	Newsprint (n)	65
	Medium	Magenta	Uncoated Offset (u)	100
	High	Cyan	Coated Offset (c)	150

TABLE 2

ACTUAL LEVELS OF SOLID INK DENSITY FOR PAPER USED

		Solid Ink Density for all Screen Rulings		
		Yellow-l	Magenta-m	Cyan-h
S.I.D. Level	Low	.45 - n .47 - u .61 - c	.65 - n .63 - u .80 - c	.45 - n .63 - u .60 - c
	Medium	.62 - n .64 - u .86 - c	.90 - n .97 - u 1.18 - c	.90 - n 1.00 - u 1.00 - c
	High	.80 - n .83 - u 1.15 - c	1.10 - n 1.20 - u 1.60 - c	1.15 - n 1.38 - u 1.42 - c

Mean solid ink density of twice replicated treatment samples ± .015

The capital letters C, D, P, and H shall represent the factors of Color, solid ink Density, type of Paper, and Halftone screen ruling respectively. The levels of each factor tested (low, medium, and high) will be indicated by the subscripts l, m, and h. The resultant factorial experiment treatment table is shown in Table 3. As an example, the treatment listed in the table as $C_m D_l P_h H_m$ will represent a sample printed with magenta ink at solid ink density of 0.80 on coated offset paper using a 100 line per inch halftone screen ruling.

The red, green, and blue filter densities obtained from each sample will be used to generate percent efficiency data for each tint. The percent efficiency data is used to generate the proportionality failure index data.

TABLE 3

GENERAL TREATMENT TABLE FOR EACH TINT

(Yellow) l									(Magenta) m									(Cyan) h									SCREEN RULING
THICKNESS l			THICKNESS m			THICKNESS h			THICKNESS l			THICKNESS m			THICKNESS h			THICKNESS l			THICKNESS m			THICKNESS h			
PAPER l	PAPER m	PAPER h	PAPER l	PAPER m	PAPER h	PAPER l	PAPER m	PAPER h	PAPER l	PAPER m	PAPER h	PAPER l	PAPER m	PAPER h	PAPER l	PAPER m	PAPER h	PAPER l	PAPER m	PAPER h	PAPER l	PAPER m	PAPER h	PAPER l	PAPER m	PAPER h	
C_l D_l P_l H_l	C_l D_l P_m H_l	C_l D_l P_h H_l	C_l D_m P_l H_l	C_l D_m P_m H_l	C_l D_m P_h H_l	C_l D_h P_l H_l	C_l D_h P_m H_l	C_l D_h P_h H_l	C_m D_l P_l H_l	C_m D_l P_m H_l	C_m D_l P_h H_l	C_m D_m P_l H_l	C_m D_m P_m H_l	C_m D_m P_h H_l	C_m D_h P_l H_l	C_m D_h P_m H_l	C_m D_h P_h H_l	C_h D_l P_l H_l	C_h D_l P_m H_l	C_h D_l P_h H_l	C_h D_m P_l H_l	C_h D_m P_m H_l	C_h D_m P_h H_l	C_h D_h P_l H_l	C_h D_h P_m H_l	C_h D_h P_h H_l	l
C_l D_l P_l H_m	C_l D_l P_m H_m	C_l D_l P_h H_m	C_l D_m P_l H_m	C_l D_m P_m H_m	C_l D_m P_h H_m	C_l D_h P_l H_m	C_l D_h P_m H_m	C_l D_h P_h H_m	C_m D_l P_l H_m	C_m D_l P_m H_m	C_m D_l P_h H_m	C_m D_m P_l H_m	C_m D_m P_m H_m	C_m D_m P_h H_m	C_m D_h P_l H_m	C_m D_h P_m H_m	C_m D_h P_h H_m	C_h D_l P_l H_m	C_h D_l P_m H_m	C_h D_l P_h H_m	C_h D_m P_l H_m	C_h D_m P_m H_m	C_h D_m P_h H_m	C_h D_h P_l H_m	C_h D_h P_m H_m	C_h D_h P_h H_m	m
C_l D_l P_l H_h	C_l D_l P_m H_h	C_l D_l P_h H_h	C_l D_m P_l H_h	C_l D_m P_m H_h	C_l D_m P_h H_h	C_l D_h P_l H_h	C_l D_h P_m H_h	C_l D_h P_h H_h	C_m D_l P_l H_h	C_m D_l P_m H_h	C_m D_l P_h H_h	C_m D_m P_l H_h	C_m D_m P_m H_h	C_m D_m P_h H_h	C_m D_h P_l H_h	C_m D_h P_m H_h	C_m D_h P_h H_h	C_h D_l P_l H_h	C_h D_l P_m H_h	C_h D_l P_h H_h	C_h D_m P_l H_h	C_h D_m P_m H_h	C_h D_m P_h H_h	C_h D_h P_l H_h	C_h D_h P_m H_h	C_h D_h P_h H_h	h

Generating and Processing Data

The density measurements for the experiment were obtained with the use of a Cosar SOS 404 reflection densitometer with a digital readout. The response for each treatment was the density obtained from the three color analyzing filters with the densitometer being calibrated to the standard supplied by the manufacturer and zeroed to the paper. In this way any spectral deviations in density readings caused by the paper can be measured without inadvertently measuring the density of the paper itself. The relationship of these density readings shall be expressed in terms of the percent efficiency of the inks;[11]

$$\text{percent efficiency} = \left[1 - \frac{M + L}{2H}\right] \times 100$$

where H is the highest density reading and M and L are the middle and low density readings. This equation is derived by adding the ratios of the low-to-high and medium-to-high densities, dividing by 2 (to find an average), and subtracting from 1 to obtain the proper value for percent efficiency. Note that if the medium and low density readings are zero the percent efficiency is one (100%).

This equation takes the three density readings and produces one response variable which can only indicate the percent efficiency for one tint. Since density readings will be taken at a 10%, 50%, and 100% tint there will be three percent efficiency numbers for each sample. These will then be used in the following equation to give an index of the amount of proportionality failure occurring in each sample:

$$\text{Index of Proportionality Failure} = \frac{(r-m) + (r-l)}{2}$$

In this case r is the percent efficiency of the solid (reference) and m and l are the percent efficiencies of the 50% and 10% tint respectively. This equation is an averaging of the differences in percent efficiency at the different tint levels as compared to the percent efficiency of the reference solid (100% tint). A certain degree of information has been sacrificed at this point to be able to derive one number for statistical manipulation. The experiment is designed, however, to create a large enough sensitivity to help compensate for this loss of information.

Analysis of Variance

Once all data points have been printed and read on the densitometer and the responses listed in the treatment tables for the amount of proportionality failure present in each, an Analysis of Variance (ANOVA) will be conducted to determine the statistical significance of each factor. The purpose for hypothesizing that there is no significant difference in the influence of each factor on proportionality failure can now be explained.

The statistical analysis of this experiment is based on a mathematical model which assumes there is no difference between factors and levels. It is expected that the results of this experiment will reject this hypothesis and support the alternate hypothesis which will show the actual significance of each factor. An 'alpha-risk' and 'beta-risk' shall be assigned to the experiment. The alpha-risk is the risk of rejecting the alternate hypothesis when it should be accepted. This shall be set at 0.05, meaning that a rejection of the hypothesis stands a 5% chance of being wrong. The beta-risk is the risk of accepting the alternate hypothesis when it should be rejected. This is also set at 0.05. The determination of alpha, and beta-risks is an arbitrary one which is set by the designer of the experiment. The alpha and beta risks chosen here are exemplary of what are most often used in statistical studies.

In order to test the validity of the hypothesis the data will be processed for the ANOVA table with the use of C-notation techniques. A components-of-variance procedure will then be used to determine the proper F-test sequence. The F-test will then show if any of the factors are significant in causing proportionality failure, and to what degree they are significant.

> We imagine a single hypothetical normal population with variance σ^2. From this population we take all possible samples of size n_1, and for each sample we find the variance s_1^2. From this same population we take all possible samples of size n_2, and find the set of sample variances s_2^2. Now, we find all possible ratios of the

paired sample variances s_1^2/s_2^2. From these ratios we construct a frequency distribution; this is called an F distribution... An F test helps us decide whether or not two processes have similar variability... Furthermore, F tests are used in the analysis of data from an experiment in which we try to discover which of several factors affect a process.[12]

C-Notation

The analysis of variance for factorial experiments can pose certain problems as far as processing the data is concerned. Using conventional procedures it would be necessary to set up 'summing over' tables for every possible paired combination of the factors being tested. From these summing over tables the data can then be processed for the actual Analysis of Variance. In order to avoid these tedious processing steps a method known as C-notation will be used to process data from the treatment tables directly to the ANOVA table. In order for the experiment to yield more information an ANOVA will be conducted for each color. In this way the affect and importance of proportionality failure can be determined for cyan, magenta and yellow. Spliting the ANOVA into three tests does not change the design of the experiment. It will mean that there are three sections, each of which is a 3^3 factorial requiring at least 27 samples each for analysis. Since the amount of proportionality failure differs for each color this design will yield the maximum amount of information possible. The following is a summary of the C-notation used in this experiment:

Factor	Levels
D_j (S.I.D.)	(low)———— (q)=3=j
P_k (Paper)	(medium)——— (r)=3=k
H_l (Halftone Ruling)	(high)———— (s)=3=l
	(replicates)–(n)=2=n

$$C_j = \sum_j \frac{T^2_{j...}}{klm} \qquad C_l = \sum_l \frac{T^2_{..l.}}{jkn}$$

$$C_k = \sum_k \frac{T^2_{.k..}}{jln}$$

$$C_{jl} = \sum_{jl} \frac{T^2_{j.l.}}{kn} = \frac{T^2_{1.1.} + T^2_{1.2.} + T^2_{1.3.} + T^2_{2.1.} + T^2_{2.2.} +}{6}$$

$$\frac{T^2_{2.3.} + T^2_{3.1.} + T^2_{3.2.} + T^2_{3.3.}}{6}$$

$$C_{jk} = \sum_{jk} \frac{T^2_{jk..}}{ln} = \frac{T^2_{11..} + T^2_{12..} + T^2_{13..} + T^2_{21..} + T^2_{22..} +}{6}$$

$$\frac{T^2_{23..} + T^2_{31..} + T^2_{32..} + T^2_{33..}}{6}$$

$$C_{kl} = \sum_{kl} \frac{T^2_{.kl.}}{jn} \quad \frac{T^2_{.11.} + T^2_{.12.} + T^2_{.13.} + T^2_{.21.} + T^2_{.22.} +}{6}$$

$$\frac{T^2_{.23.} + T^2_{.31.} + T^2_{.32.} + T^2_{.33.}}{6}$$

$$C_{jkl} = \sum_{jkl} \frac{T^2_{jkl.}}{n} = \sum \frac{(\text{cell totals})^2}{n}$$

$$C = \frac{T^2_{....}}{jkln} = \sum \frac{(\text{individual responses})^2}{54} = \text{'correction factor'}$$

The symbol T represents a sum total of the responses of certain levels of each factor. For example, $T^2_{j...}$, represents the sum of each level of j totaled over all levels of k, l, and n. This would yield three sums, one each for the low, medium, and high levels of factor j.

The numbers generated from these equations will be used in the analysis of variance. The general ANOVA table which will be used in all analysis of variance is shown in Table 4.

With this experiment it will be necessary to draw conclusions for the factors of screen ruling and solid ink density over a continuous range rather than at just the levels tested. This will mean that these are random factors while paper will be a fixed factor. If all factors were fixed it would be possible to test each factor against error in the F-ratio test for significance. Since the conclusions will be based on both fixed and random factors, a components of variance algorithm must be applied in order to determine the proper F-ratio sequence; (see Table 5).

TABLE 4

GENERAL ANOVA FOR EACH COLOR

Source	Sums of Squares	Degrees of freedom (ν=n-1)	Binomial expansion	Sum of Squares (from binomial)	Mean Square (=s.s.$\div\nu$)	F-ratio
(S.I.D.)D_j	S_j	2	j-1	C_j-C		
P_k (paper)	S_k	2	k-1	C_k-C		
H_l (Halftone)	S_l	2	l-1	C_l-C		
$(DP)_{jk}$ (S.I.D. - paper interaction)	S_{jk}	4	(j-1)(k-1)	$C_{jk}-C_j-C_k+C$		
$(DH)_{jl}$ (Halftone - S.I.D. interaction)	S_{jl}	4	(j-1)(l-1)	$C_{jl}-C_j-C_l+C$		
$(PH)_{kl}$ (Paper - Halftone interaction)	S_{kl}	4	(k-1)(l-1)	$C_{kl}-C_k-C_l+C$		
$(DPH)_{jkl}$ (three-way interaction)	S_{jkl}	8	(j-1)(k-1)(l-1)	$C_{jkl}-C_{jk}-C_{jl}-C_{kl}$ $+C_j+C_k+C_l-C$		
$\epsilon_{(jkl)}$ (error nested in jkl)	$S_{n(jkl)}$	27	(n-1)(jkl)	$C_{jkln}-C_{jkl}$		
Total		53				

TABLE 5

COMPONENTS OF VARIANCE ALGORITHM FOR PROPER F-RATIO SEQUENCE

Source	(SID) Random j=3	(Paper) Fixed k=3	(Screen Ruling) Random l=3	(Replicates) Random n=2	E.M.S.
D_j	1	3	3	2	$18\sigma_D^2 + 6\sigma_{DH}^2 + \sigma_\epsilon^2$
P_k	3	0	3	2	$18\sigma_P^2 + 6\sigma_{DP}^2 + 6\sigma_{PH}^2 + 2\sigma_{DPH}^2 + \sigma_\epsilon^2$
H_l	3	3	1	2	$18\sigma_H^2 + 6\sigma_{DH}^2 + \sigma_\epsilon^2$
$(DP)_{jk}$	1	0	3	2	$6\sigma_{DP}^2 + 2\sigma_{DPH}^2 + \sigma_\epsilon^2$
$(DH)_{jl}$	1	3	1	2	$6\sigma_{DH}^2 + \sigma_\epsilon^2$
$(PH)_{kl}$	3	0	1	2	$6\sigma_{PH}^2 + 2\sigma_{DPH}^2 + \sigma_\epsilon^2$
$(DPH)_{jkl}$	1	0	1	2	$2\sigma_{DPH}^2 + \sigma_\epsilon^2$
$\epsilon_{(jkl)}$	1	1	1	1	σ_ϵ^2

Note: Components of Variance Algorithm can be found in: <u>Statistics, an Introduction</u> by Albert D. Rickmers and Hollis N. Todd, (McGraw-Hill Book Co., 1967), pp. 179 - 197.

Now the test sequence has been established. The F-ratio to test the significance of halftone screen ruling, for example, will now be:

$$\frac{\text{mean square for } H_l}{\text{mean square for } (DH)_{jl}}$$

with the critical F value being found in an F-distribution table[13]. This critical value will be found from the degrees of freedom of each factor, and the alpha-risk assigned to the experiment. In the foregoing example H would be $F_{2,4,.05}$ which has a value of 6.9443 in the table.

The F-ratio test for the significance of paper must be dealt with differently since there is no other factor with which to test it. In this case a composite mean square method will be used to find the F-ratio, and the degrees of freedom (ν_1 and ν_2) for generating the critical F-value.

Composite mean square F-test for the significance of Paper in its affect on Proportionality Failure:

$$\left(\frac{\text{mean square } P_k + \text{mean square } \epsilon_{n(jkl)}}{\text{mean square } (DP)_{jk} + \text{mean square } (PH)_{kl} + \text{mean square } (DPH)_{jkl}}\right)$$

Degrees of Freedom (ν_1 and ν_2) for critical F-value:

$$\nu_1 ; \left(\frac{(\text{m.s.}P_k)^2}{P} + \frac{(\text{m.s. } \epsilon_{(jlk)})^2}{\epsilon} = \frac{(\text{m.s.}P_k + \text{m.s. } \epsilon_{(jkl)})^2}{1} \right) \text{INT}$$

$$\nu_2 ; \left(\frac{(\text{m.s.}(DP)_{jk})^2}{DP} + \frac{(\text{m.s.}(PH)_{kl})^2}{PH} + \frac{(\text{m.s.}(DPH)_{jkl})^2}{DPH} = \frac{(\text{m.s.}(DP)_{jk} + \text{m.s.}(PH)_{kl} + \text{m.s.}(DPH)_{jkl})^2}{2} \right) \text{INT}$$

In the above equations INT is included to signify that the number obtained is rounded off to the nearest whole integer.

Results

Treatment Tables

TABLE 6

PERCENT EFFICIENCY DATA FOR YELLOW INK

Solid Ink Density										
l (.45)(.47)(.61)			m (.62)(.64)(.86)			h (.80)(.83)(1.15)				
Paper			Paper			Paper				
news	un-coat	coated	news	un-coat	coated	news	un-coat	coated		
.85 .85	.89 .88	.88 .88	.81 .81	.88 .88	.86 .86	.85 .83	.88 .86	.83 .81	10% tint	65
.91 .91	.94 .94	.94 .94	.89 .89	.93 .93	.91 .92	.93 .92	.92 .92	.92 .91	50% tint	
.95 .94	.97 .97	.97 .96	.93 .91	.96 .95	.95 .96	.95 .95	.94 .94	.95 .95	100% tint	
.86 .86	.88 .88	.90 .90	.85 .85	.88 .89	.86 .87	.87 .86	.88 .88	.84 .85	10% tint	100
.92 .93	.94 .95	.93 .95	.90 .91	.95 .95	.93 .94	.90 .89	.90 .93	.91 .91	50% tint	
.95 .95	.95 .96	.97 .97	.94 .94	.96 .96	.95 .95	.94 .94	.94 .95	.95 .95	100% tint	
.86 .86	.89 .89	.92 .91	.87 .86	.89 .89	.90 .90	.88 .86	.89 .89	.90 .90	10% tint	150
.91 .90	.95 .95	.95 .95	.93 .92	.96 .96	.93 .93	.92 .92	.91 .90	.92 .93	50% tint	
.94 .92	.97 .96	.97 .96	.94 .94	.96 .97	.95 .96	.95 .95	.93 .93	.96 .95	100% tint	

Screen Ruling

TABLE 7

PERCENT EFFICIENCY DATA FOR MAGENTA INK

Solid Ink Density										
l (.65)(.63)(.80)			m (.90)(.97)(1.18)			h (1.10)(1.20)(1.60)				
Paper			Paper			Paper				
news	un- coat	coated	news	un- coat	coated	news	un- coat	coated		
.38 .38	.37 .37	.42 .43	.36 .36	.35 .35	.40 .42	.32 .35	.32 .33	.41 .41	10% tint	65
.43 .45	.38 .39	.44 .45	.43 .42	.41 .40	.41 .44	.36 .40	.34 .34	.43 .41	50% tint	
.57 .57	.49 .48	.63 .62	.56 .56	.49 .49	.61 .61	.56 .56	.47 .46	.62 .63	100% tint	
.45 .44	.38 .38	.45 .42	.42 .42	.39 .39	.44 .44	.38 .39	.39 .38	.44 .43	10% tint	100
.48 .48	.40 .39	.52 .48	.47 .46	.41 .42	.49 .48	.41 .42	.40 .39	.46 .46	50% tint	
.57 .58	.47 .47	.60 .60	.55 .56	.50 .51	.60 .62	.56 .56	.49 .50	.62 .62	100% tint	
.49 .50	.43 .43	.51 .50	.49 .50	.41 .41	.48 .47	.40 .42	.42 .42	.47 .45	10% tint	150
.51 .52	.45 .46	.57 .56	.51 .50	.46 .45	.50 .49	.45 .46	.43 .43	.49 .47	50% tint	
.58 .57	.47 .49	.60 .61	.58 .57	.47 .48	.60 .60	.57 .56	.48 .49	.61 .61	100% tint	

Screen Ruling

TABLE 8

PERCENT EFFICIENCY DATA FOR CYAN INK

Solid Ink Density										
l (.45)(.63)(.60)			m (.90)(1.00)(1.00)			h (1.15)(1.38)(1.42)				
Paper			Paper			Paper				
news	un-coat	coated	news	un-coat	coated	news	un-coat	coated		
.47 .46	.40 .39	.67 .67	.41 .42	.33 .33	.49 .50	.40 .40	.29 .30	.41 .40	10% tint	65
.66 .65	.55 .55	.75 .71	.61 .62	.48 .48	.60 .62	.53 .55	.46 .49	.58 .58	50% tint	
.73 .74	.65 .65	.80 .79	.73 .72	.65 .66	.78 .77	.69 .69	.63 .61	.78 .79	100% tint	
.52 .50	.51 .50	.71 .70	.49 .50	.44 .44	.68 .68	.46 .46	.40 .42	.62 .64	10% tint	100 Screen Ruling
.66 .64	.65 .63	.75 .74	.63 .64	.62 .61	.70 .69	.60 .60	.56 .58	.64 .67	50% tint	
.71 .72	.68 .69	.80 .80	.72 .71	.69 .69	.80 .81	.67 .66	.67 .66	.81 .80	100% tint	
.55 .57	.61 .60	.75 .75	.55 .55	.56 .56	.69 .70	.54 .54	.53 .50	.67 .65	10% tint	150
.67 .68	.63 .62	.73 .76	.67 .66	.64 .64	.70 .70	.66 .64	.62 .60	.69 .67	50% tint	
.74 .73	.66 .67	.80 .80	.69 .70	.69 .68	.79 .79	.69 .70	.67 .68	.77 .79	100% tint	

Note: To obtain percent efficiency all of the numbers in the table should be multiplied by 100.

TABLE 9

PROPORTIONALITY FAILURE INDEX FOR YELLOW INK

Solid Ink Density:	l			m			h				
	(.45)	(.47)	(.61)	(.62)	(.64)	(.86)	(.80)	(.83)	(1.15)		
Paper	n	u	c	n	u	c	n	u	c		Screen Ruling
	* .07	.06	.06	.08	* .05	.07	.08	.05	* .08	1st replicate	65
	.06	.05	.05	.06	.04	.06	.06	.04	.09	2nd replicate	65
	(.13)	(.11)	(.11)	(.14)	(.09)	(.13)	(.14)	(.09)	(.17)	cell total	65
	* .06	.05	.06	.06	* .04	.05	.07	.04	* .08	1st replicate	100
	.05	.04	.05	.07	.05	.06	.06	.05	.07	2nd replicate	100
	(.11)	(.09)	(.11)	(.13)	(.09)	(.11)	(.13)	(.09)	(.15)	cell total	100
	* .06	.04	.03	.05	* .04	.04	.06	.03	* .05	1st replicate	150
	.04	.05	.04	.04	.05	.05	.05	.02	.04	2nd replicate	150
	(.10)	(.09)	(.07)	(.09)	(.09)	(.09)	(.11)	(.05)	(.09)	cell total	150

* a curve of the wanted density versus the unwanted density for varying tints can be found in Appendix A for these samples.

TABLE 10

PROPORTIONALITY FAILURE INDEX FOR MAGENTA INK

	Solid Ink Density									
	l			m			h			
	(.65)	(.63)	(.80)	(.90)	(.97)	(1.18)	(1.10)	(1.20)	(1.60)	
	Paper			Paper			Paper			
Screen Ruling	n	u	c	n	u	c	n	u	c	
65	*.17	.10	.20	.17	*.12	.18	.23	.13	*.22	1st replicate
	.16	.12	.18	.16	.11	.21	.19	.14	.20	2nd replicate
	(.33)	(.22)	(.38)	(.33)	(.23)	(.39)	(.42)	(.27)	(.42)	cell total
100	*.12	.08	.15	.10	*.10	.16	.17	.12	*.18	1st replicate
	.10	.09	.11	.12	.11	.14	.16	.10	.17	2nd replicate
	(.22)	(.17)	(.26)	(.22)	(.21)	(.30)	(.33)	(.22)	(.35)	cell total
150	*.08	.03	.08	.07	*.04	.11	.15	.07	*.15	1st replicate
	.06	.05	.06	.09	.05	.12	.12	.06	.13	2nd replicate
	(.14)	(.08)	(.14)	(.16)	(.09)	(.23)	(.27)	(.13)	(.28)	cell total

* a curve of the wanted density versus the unwanted density for varying tints can be found in Appendix A for these samples.

TABLE 11

PROPORTIONALITY FAILURE INDEX FOR CYAN INK

Solid Ink Density										
l			m			h				
(.45)	(.63)	(.60)	(.90)	(1.00)	(1.00)	(1.15)	(1.38)	(1.42)		
Paper			Paper			Paper				
n	u	c	n	u	c	n	u	c		
* .17	.18	.09	.22	* .25	.21	.22	.26	* .29	1st replicate	Screen Ruling 65
.19	.17	.10	.20	.26	.24	.23	.22	.30	2nd replicate	
(.36)	(.35)	(.19)	(.42)	(.51)	(.45)	(.45)	(.48)	(.59)	cell total	
* .12	.13	.07	.16	* .16	.13	.14	.16	* .15	1st replicate	Screen Ruling 100
.15	.10	.08	.14	.17	.11	.13	.19	.18	2nd replicate	
(.27)	(.23)	(.15)	(.30)	(.33)	(.24)	(.27)	(.35)	(.33)	cell total	
* .13	.04	.05	.08	* .08	.09	.11	.13	* .09	1st replicate	Screen Ruling 150
.11	.06	.06	.10	.09	.10	.09	.10	.13	2nd replicate	
(.24)	(.10)	(.11)	(.18)	(.17)	(.19)	(.20)	(.23)	(.22	cell total	

* a curve of the wanted density versus the unwanted density for varying tints can be found in Appendix A for these samples.

Analysis of Variance

The following are the C-notation figures for the sums of squares, which will be used to test for significance with yellow ink; (see Table 12).

$$C_j = \sum_j \frac{T^2_{j...}}{kln} = \frac{92^2 + 96^2 + 102^2}{18} = 1560.22$$

$$C_k = \sum_k \frac{T^2_{.k..}}{jln} = \frac{108^2 + 79^2 + 103^2}{18} = 1584.11$$

$$C_l = \sum_l \frac{T^2_{..l.}}{jkn} = \frac{111^2 + 101^2 + 78^2}{18} = 1589.22$$

$$C_{jl} = \sum_{jl} \frac{T^2_{j.l.}}{kn} = \frac{35^2+36^2+40^2+37^2+33^2+31^2+26^2+27^2+25^2}{6} = 1595.00$$

$$C_{jk} = \sum_{jk} \frac{T^2_{jk..}}{ln} = \frac{34^2+29^2+29^2+36^2+27^2+33^2+38^2+23^2+41^2}{6} = 1601.00$$

$$C_{kl} = \sum_{kl} \frac{T^2_{.kl.}}{jn} = \frac{41^2+29^2+41^2+37^2+27^2+36^2+30^2+23^2+25^2}{6} = 1608.50$$

$$C_{jkl} = \sum_{jkl} \frac{T^2_{jkl.}}{n} = \sum \frac{(\text{cell totals})^2}{2} = 1646.00$$

$$C = \frac{T^2_{....}}{jkln} = \frac{(\text{total response for experiment})^2}{54} = 1557.41$$

$$\text{Error} = C_{jkln} - C_{jkl} = 18.00$$

$$C_{jkln} = \sum_{jkln} \frac{T^2_{jkln}}{1} = \sum \frac{(\text{Each response})^2}{1} = 1664.00$$

TABLE 12

ANOVA FOR YELLOW INK

Source	ν	Sum of Squares	Mean Square	F-ratio (with critical F-value)
(SID) D_j	2	$C_j - C =$ 2.81	1.41	($F_{2,4,.05}$ = 6.9443) 1.91 - not significant
(Paper) P_k	2	$C_k - C =$ 26.70	13.35	($F_{2,9,.05}$ = 4.2565 0.89 - not significant
(Screen Ruling)H_l	2	$C_l - C =$ 31.81	15.91	($F_{2,4,.05}$ = 6.9443) 21.50 * *
$(DP)_{jk}$	4	$C_{jk} - C_j - C_k + C =$ 37.86	9.46	($F_{4,8,.05}$ = 3.8378) 4.17 * *
$(DH)_{jl}$	4	$C_{jl} - C_j - C_l + C =$ 2.97	0.74	($F_{4,27,.05}$= 2.7278) 1.10 - not significant
$(PH)_{kl}$	4	$C_{kl} - C_k - C_l + C =$ 16.36	4.09	($F_{4,8,.05}$= 3.8378) 1.80 - not significant
$(DPH)_{jkl}$	8	$C_{jkl} - C_{jk} - C_{jl} - C_{kl} + C_j + C_k + C_l - C =$ 18.15	2.27	($F_{8,27,.05}$= 2.3053) 3.39 * *
$\epsilon_{n(jkl)}$	27	$C_{jkln} - C_{jkl} =$ 18.00	0.67	
Total	53			

** denotes significant factor with alpha-risk of 0.05.

The following are the C-notation figures for the sums of squares which will be used to test for significance with magenta ink; (see Table 13).

$$C_j = \sum_j \frac{T^2_{j...}}{kln} = 8702.94$$

$$C_k = \sum_k \frac{T^2_{.k..}}{jln} = 8912.94$$

$$C_l = \sum_l \frac{T^2_{..l.}}{jkn} = 9138.28$$

$$C_{jl} = \sum_{jl} \frac{T^2_{j.l.}}{kn} = 9312.17$$

$$C_{jk} = \sum_{jk} \frac{T^2_{jk..}}{ln} = 9106.83$$

$$C_{kl} = \sum_{kl} \frac{T^2_{.kl.}}{jn} = 9532.17$$

$$C_{jkl} = \sum_{jkl} \frac{T^2_{jkl.}}{n} = \sum \frac{(\text{cell totals})^2}{2} = 9744.50$$

$$C = \frac{T^2_{....}}{jkln} = \frac{(\text{total response for experiment})^2}{54} = 8537.80$$

$$\text{Error} = C_{jkln} - C_{jkl} = 54.50$$

$$C_{jkln} = \sum_{jkln} \frac{T^2_{jkln}}{1} = \sum \frac{(\text{each response})^2}{1} = 9799.00$$

TABLE 13

ANOVA FOR MAGENTA INK

Source	ν	Sum of Squares	Mean Square	F-ratio (with critical F-value)
(SID) D_j	2	$C_j - C = 165.14$	82.57	$(F_{2,4,.05} = 6.9443)$ 37.70 * *
(Paper) P_k	2	$C_k - C = 375.14$	187.57	$(F_{2,6,.05} = 5.1433)$ 7.22 * *
(Screen Ruling) H_l	2	$C_l - C = 600.48$	300.24	$(F_{2,4,.05} = 6.9443)$ 137.10 * *
$(DP)_{jk}$	4	$C_{jk} - C_j - C_k + C = 81.42$	20.36	$(F_{4,8,.05} = 3.8378)$ 16.83 * *
$(DH)_{jl}$	4	$C_{jl} - C_j - C_l + C = 8.57$	2.19	$(F_{4,27,.05} = 2.7278)$ 1.08-not significant
$(PH)_{kl}$	4	$C_{kl} - C_k - C_l + C = 18.75$	4.69	$(F_{4,8,.05} = 3.8378)$ 3.88 * *
$(DPH)_{jkl}$	8	$C_{jkl} - C_{jk} - C_{jl} - C_{kl} +$ $C_j + C_k + C_l - C = 9.69$	1.21	$(F_{8,27,.05} = 2.3053)$ 0.60-not significant
$\epsilon_{n(jkl)}$	27	$C_{jkln} - C_{jkl} = 54.50$	2.02	
Total	53			

** denotes significance with alpha risk of 0.05.

The following are the C-notation figures for the sums of squares which will be used to test for significance with cyan ink; (see Table 14)

$$C_j = \sum_j \frac{T^2_{j...}}{kln} = 11954.72$$

$$C_k = \sum_k \frac{T^2_{.k..}}{jln} = 11610.83$$

$$C_l = \sum_l \frac{T^2_{..l.}}{jkn} = 12905.83$$

$$C_{jl} = \sum_{jl} \frac{T^2_{j.l.}}{kn} = 13372.17$$

$$C_{jk} = \sum_{jk} \frac{T^2_{jk..}}{ln} = 12159.83$$

$$C_{kl} = \sum_{kl} \frac{T^2_{.kl.}}{jn} = 12963.83$$

$$C_{jkl} = \sum_{jkl} \frac{T^2_{jkl.}}{n} = \sum \frac{(\text{cell totals})^2}{2} = 13678.50$$

$$C = \frac{T^2_{....}}{jkln} = \frac{(\text{total response for experiment})^2}{54} = 11586.69$$

$$\text{Error} = C_{jkln} - C_{jkl} = 64.50$$

$$C_{jkln} = \sum_{jkln} \frac{T^2_{jkln}}{1} = \sum \frac{(\text{each response})^2}{1} = 13743.00$$

TABLE 14

ANOVA FOR CYAN INK

Source	ν	Sum of Squares	Mean Square	F-ratio (with critical F-value)
(SID) D_j	2	$C_j - C = 368.03$	184.02	($F_{2,4,.05} = 6.9443$) 7.49 * *
(Paper) P_k	2	$C_k - C = 24.14$	12.07	($F_{2,7,.05} = 4.7374$) 0.23-not significant
(Screen Ruling) H_l	2	$C_l - C = 1319.14$	659.57	($F_{2,4,.05} = 6.9443$) 26.83 * *
$(DP)_{jk}$	4	$C_{jk} - C_j - C_k = 180.97$	45.24	($F_{4,8,.05} = 3.8378$) 5.37 * *
$(DH)_{jl}$	4	$C_{jl} - C_j - C_l = 98.31$	24.58	($F_{4,27,.05} = 2.7278$) 10.28 * *
$(PH)_{kl}$	4	$C_{kl} - C_k - C_l = 33.86$	8.47	($F_{4,8,.05} = 3.8378$) 1.01-not significant
$(DPH)_{jkl}$	8	$C_{jkl} - C_{jk} - C_{jl} - C_{kl} + C_j + C_k + C_l - C = 67.36$		($F_{8,27,.05} = 2.3053$) 3.52 * *
$\epsilon_{n(jkl)}$	27	$C_{jkln} - C_{jkl} = 64.50$	2.39	
Total	53			

** denotes significance with alpha risk of 0.05.

Paper Surface Efficiency

In order to try and correlate the amount of proportionality failure occurring with the paper being used, a Paper Surface Efficiency test[14] was conducted. The procedure involved the determination of the gloss and the absorption of the paper samples used in the experiment. Gloss was measured on a glossimeter and the absorption was determined by finding the densities produced on each paper sample after having performed a K & N ink test. From the density readings, the absorption of the paper was found with the GATF Paper Factors Conversion Chart. The paper surface efficiency was found by plotting the gloss and absorption for each paper sample on the GATF Paper Surface Efficiency Chart. The results of the experiment are seen in Table 15.

TABLE 15

PAPER SURFACE EFFICIENCY OF SAMPLES USED

Paper	K & N % Reflectance	Absorption	Paper Gloss	Paper Surface Efficiency
newsprint	39	81	18	18
uncoated	49	68	14	32
coated	74	35	58	62

Paper absorptivity = 1-1/3 (100 - K & N %)

FOOTNOTES FOR CHAPTER III

[11]Frank Preucil, "New Materials and Methods for Color Reproduction," GATF, Reports of Progress During 1958, (1959).

[12]Albert D. Rickmers and Hollis N. Todd, Statistics, an Introduction, (McGraw-Hill Book Company, 1967), p. 114.

[13]Ibid., p. 559.

[14]Frank Preucil, "A New Method of Rating the Efficiency of Paper for Color Reproduction," GATF, Reports of Progress, Number 60.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Significant Factors

Yellow Ink

Upon close examination of the results there are some interesting and unusual findings. With yellow ink both solid ink density and paper were found to be insignificant in their influence on proportionality failure. Surprisingly enough the interaction between these two factors was found to be statistically significant, implying that changes in paper and solid ink density together may cause a certain amount of proportionality failure. The other factors that were found to be significant were halftone screen ruling and the three factor interaction (paper, solid ink density, and halftone ruling).

Practical Considerations. While finding significance can prove to be statistically important the practical effects may be quite different. Yellow ink is the purest of the three process inks and is therefore less prone to proportionality failure than either magenta or cyan. It is necessary to now ask if the effects of proportionality failure for yellow ink warrant any practical considerations. In Appendix A are the proportionality failure graphs (wanted density vs. unwanted densities for all concentrations of colorant) for the yellow, magenta, and cyan inks used in the experiment. The graphs for yellow ink indicate much less proportionality failure than the other two colors. So, relative to magenta and cyan, the proportionality failure of yellow ink may not be important, that is color correction modifications need not take into account the proportionality failure exhibited by yellow ink.

Cyan Ink

Of all the factors tested with cyan ink, only paper had no influence on proportionality failure. Of the interaction affects only the interaction of paper, and halftone screen ruling were found to be insignificant. For an interaction to be insignificant it means that changes in the two factors (in this case, paper and screen ruling) together will not induce any unusually large affects which would influence or cause proportionality failure.

Practical Considerations. Of the factors that were significant some were close to being insignificant (close to the critical F-value) raising questions as to their practical importance. Included among these marginal factors were solid ink density, and the three factor interaction (paper, solid ink density, and screen ruling). Since all of these conclusions are directed towards possible modifications in color correction methods, it would have to be concluded that, for cyan ink, changes in the solid ink density might not warrant changes in color correction methods even though the factor was found to be significant.

Magenta Ink

All of the primary factors for magenta ink (SID, paper, and screen ruling) were found to be significant. Of the interaction affects, solid ink density - screen ruling and the three factor interaction were found to be insignificant. The F-value for the interaction of paper and screen ruling was found to be very close to the critical F-value and falls into the category of being a marginally significant interaction factor.

Discussion

A list of factors which influenced proportionality failure was given earlier in this thesis which was cited from John Yule. This experiment has found evidence to suggest that certain factors do not, in fact, influence this phenomenon, or that they may not be as important as was first suspected. The influence of paper, for example, was found significant only with magenta ink. This finding seems reasonable and is only valid for the types of paper used in this experiment. It must be remembered that the paper does influence the appearance of the final color and, hence, color correction requirements, but proportionality failure must not be confused with the paper's influence in changing the red, green, and blue filter densities of a solid. So that, while paper is a factor which could change color correction requirements, paper's influence on proportionality failure is not (except for magenta ink).

Of the factors tested, halftone screen ruling was the most important factor for all inks tested while solid ink density was the second most important factor. Of the inks tested, cyan and magenta exhibited the most proportionality failure. For magenta ink the conditions which produced the least amount of failure were with the 150 line screen ruling at a solid ink density of 0.63 (low level) on uncoated paper (see Table 7). For cyan ink the least amount of proportionality failure occurred under the same conditions (see Table 8). These results support the alternate hypothesis statement for solid ink density and screen ruling but not for paper. The correlation between proportionality failure and Paper Surface Efficiency could not be established. It must be concluded that the P.S.E. test is not valid for determining proportionality failure levels on different papers.

The proportionality failure occurring in yellow ink was very low overall. From the ANOVA, the graphs of proportionality failure (Appendix A), and the graphs of wanted-and-unwanted ratios versus screen ruling or solid ink density (Appendix B and C), the importance of proportionality failure in possible color correction modifications is considered negligible for yellow ink.

Recommendations

The statistical testing for significance will certainly indicate which factors are significant and to what degree. However, the relative importance of these results to practical applications must now be determined. While this experiment was not devoted quantitatively to this end, certain implications and recommendations for further research can be made.

This experiment attempted, and succeeded, to determine which factors and interactions were important, and to what degree, in causing proportionality failure. The question which this paper did not concern itself was whether or not the affects of proportionality failure would dictate any changes in color correction techniques or requirements in photographic masking. To illustrate, let us consider the most widely used method for determining the percent mask needed for a particular ink. The percent correction necessary is dictated by the equation:

$$\frac{\text{highest unwanted density}}{\text{wanted density}}$$

So, for the yellow ink the percent mask would be:[15]

$$\frac{\text{Density}_B \text{ of magenta ink}}{\text{Density}_G \text{ of magenta ink}}$$

Evaluation of a solid patch will indicate how long the A-B density range of the mask needs to be in order to obtain a sufficient amount of color correction and the proper filter to be used. But the evaluation of a solid patch will only yield information which is valid in solid areas, not highlight or midtone areas where the unwanted density would be higher and the percent mask would also need to be higher. If the evaluation were to be made at say a 40% tint, the affects of proportionality failure would be taken into account automatically. This procedure could be compared with the normal techniques used to determine if it produces better results in highlight and midtone areas. This kind of procedure may prove to be valuable for reproductions needing critical highlight rendition.

Furthermore, studies could be conducted to determine how much (if any) color correction modifications are necessary based on how much proportionality failure is occurring with a particular ink, on a particular paper. For example, the interaction of solid ink density and screen ruling was found to be significant in its influence on proportionality failure with cyan ink (Table 11). The question which might be valuable to answer is how much color correction modification is necessary for a given change in either screen ruling or solid ink density, or both. If one could quantify the amount of change needed, based on the affects of proportionality failure, guidelines for percent mask or filter changes might be established in order to improve the final results when a printer changes screen ruling or solid ink density.

FOOTNOTES FOR CHAPTER IV

[15]Miles Southworth, Color Separation Techniques, (North American Publishing Co., 1974), pp. 33, 159.

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APPENDIX A

APPENDIX A

On the following pages are the proportionality failure curves (wanted density vs. unwanted density) for the samples indicated in Table 6. In each case the dotted straight line represents the ideal situation where the proportionality rule holds. Note how, for the yellow ink, there is very little proportionality failure even with coarse screen rulings on newsprint (the closer the graph comes to the ideal straight line, the less is the proportionality failure).

In these curves D_r, D_g, and D_b refer to the red, green, and blue filter densities, respectively.

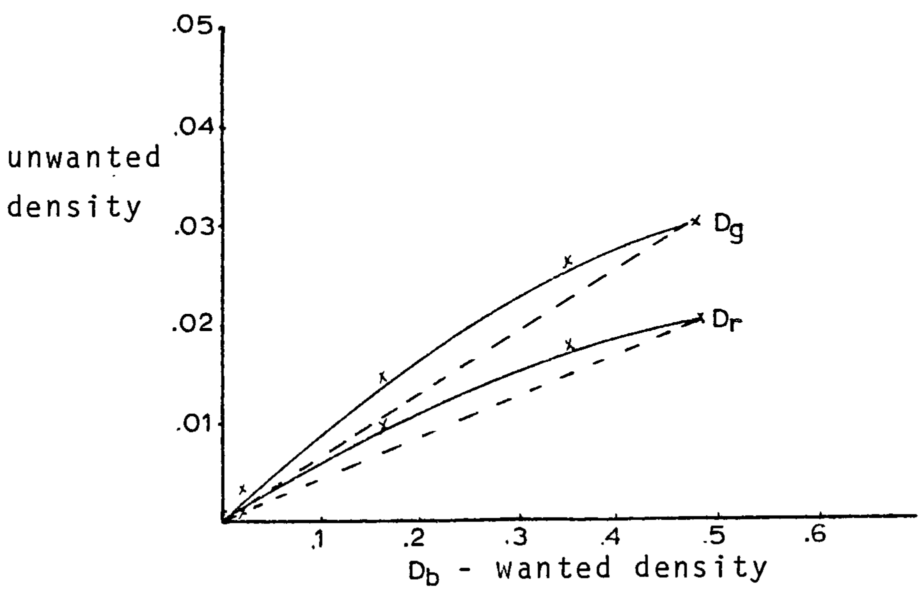

Figure A-1. Proportionality curve. Yellow - SID 0.45 - newsprint - 65 lines/inch.

APPENDIX A

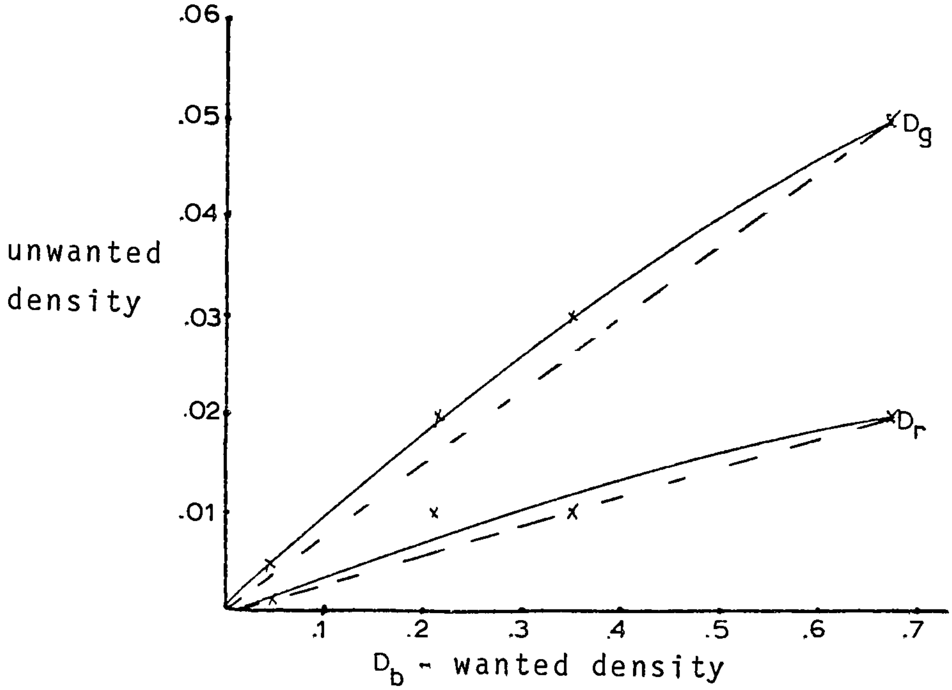

Figure A-2. Proportionality curve. Yellow - SID 0.64 - uncoated - 65 lines/inch.

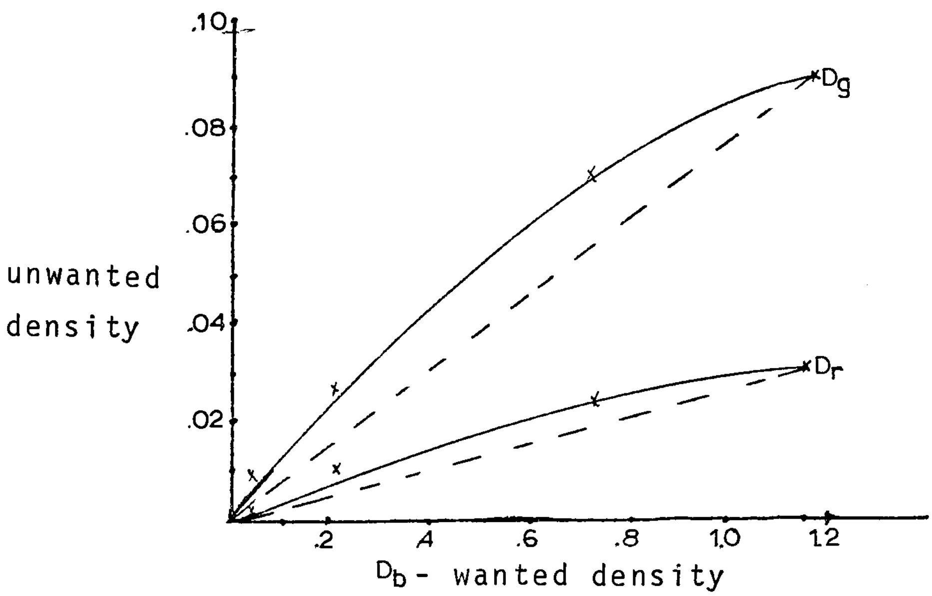

Figure A-3. Proportionality curve. Yellow - SID 1.15 - coated - 65 lines/inch.

APPENDIX A

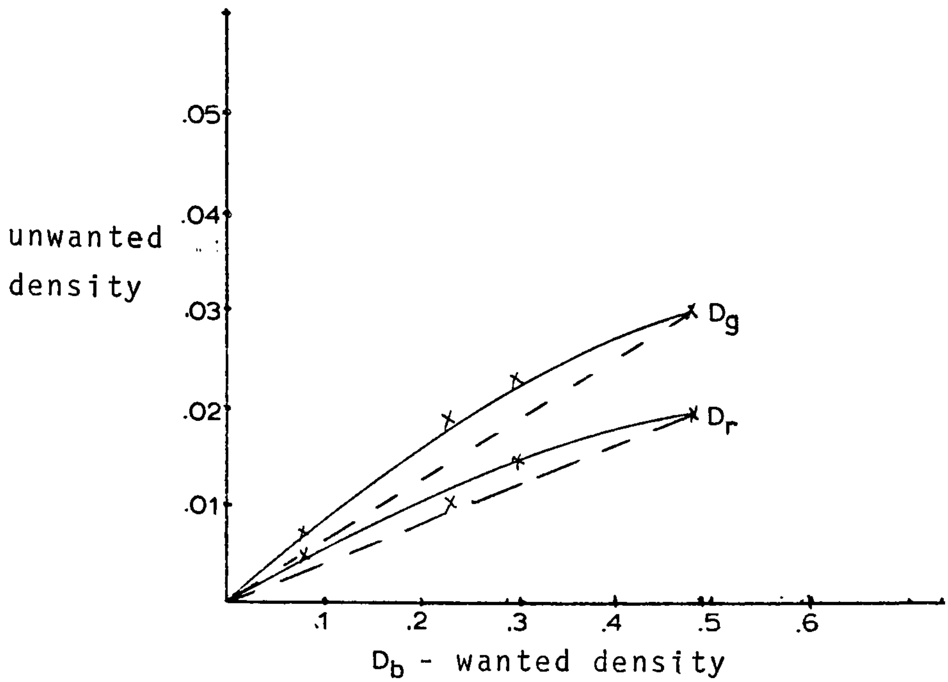

Figure A-4. Proportionality curve. Yellow - SID 0.45 - newsprint - 100 lines/inch.

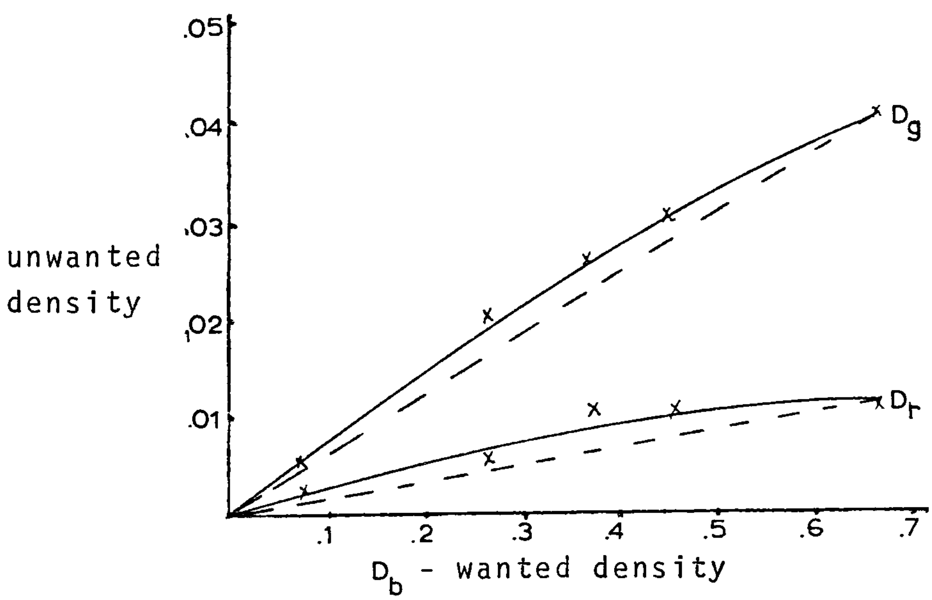

Figure A-5. Proportionality curve. Yellow - SID 0.64 - uncoated - 100 lines/inch.

APPENDIX A

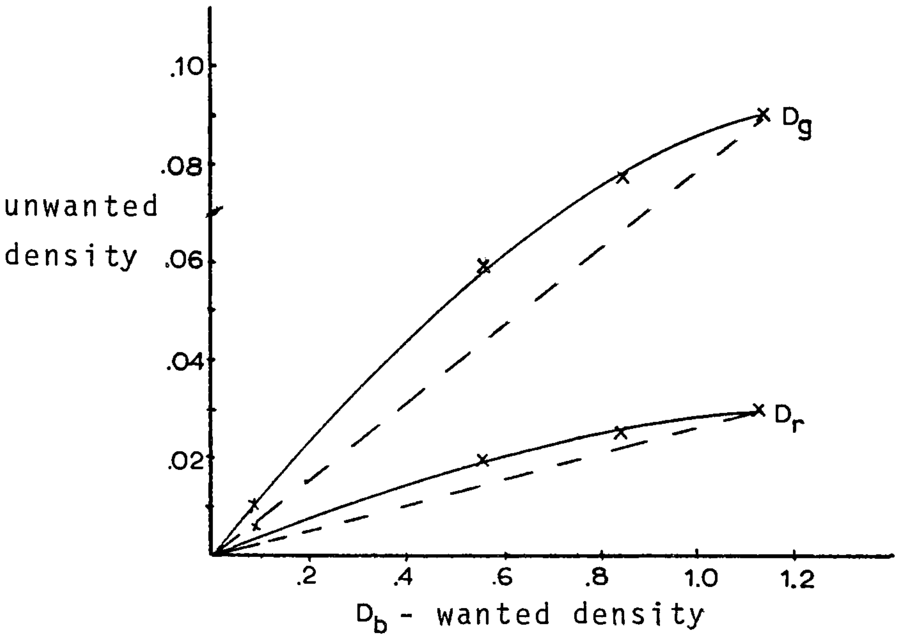

Figure A-6. Proportionality curve. Yellow - SID 1.15 - coated - 100 lines/inch.

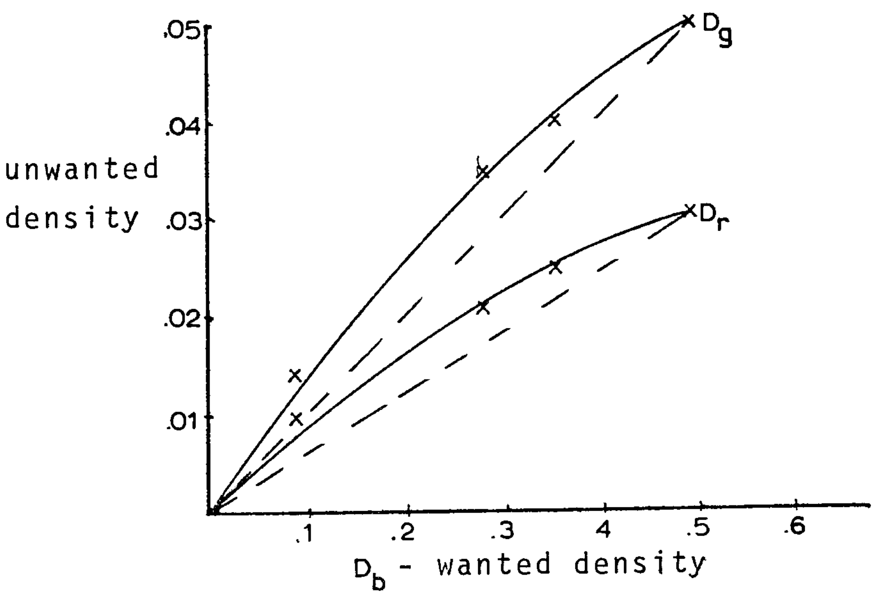

Figure A-7. Proportionality curve. Yellow - SID 0.45 - newsprint - 150 lines/inch.

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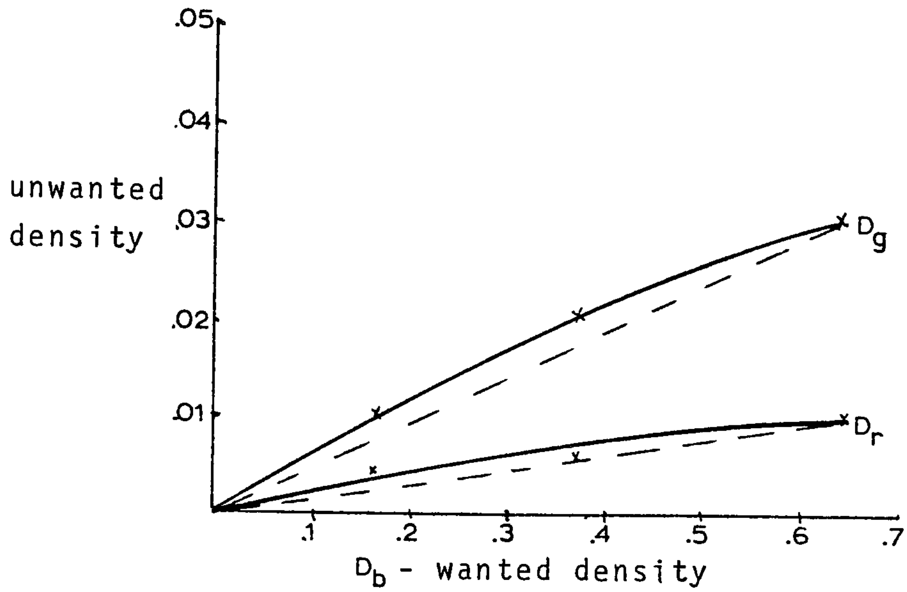

Figure A-8. Proportionality curve. Yellow - SID 0.64 - uncoated - 150 lines/inch.

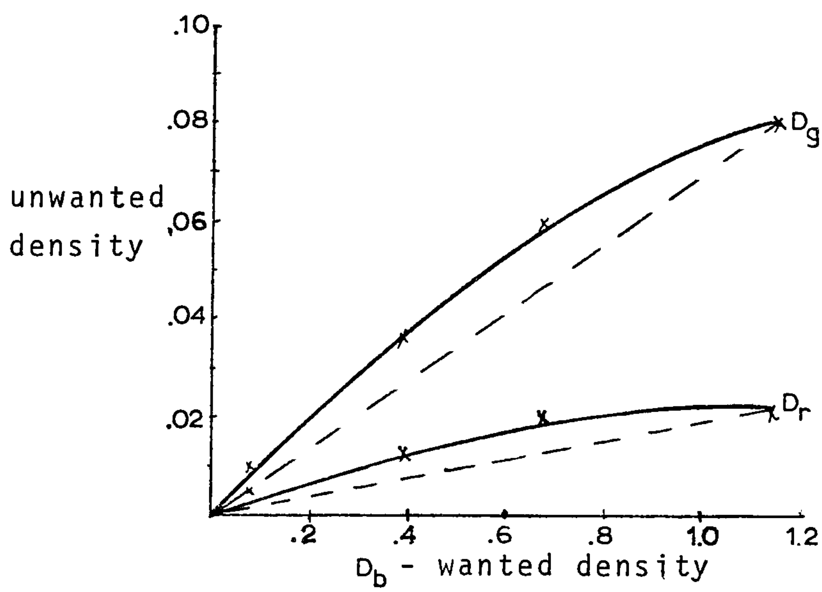

Figure A-9. Proportionality curve. Yellow - SID 1.15 - coated - 150 lines/inch.

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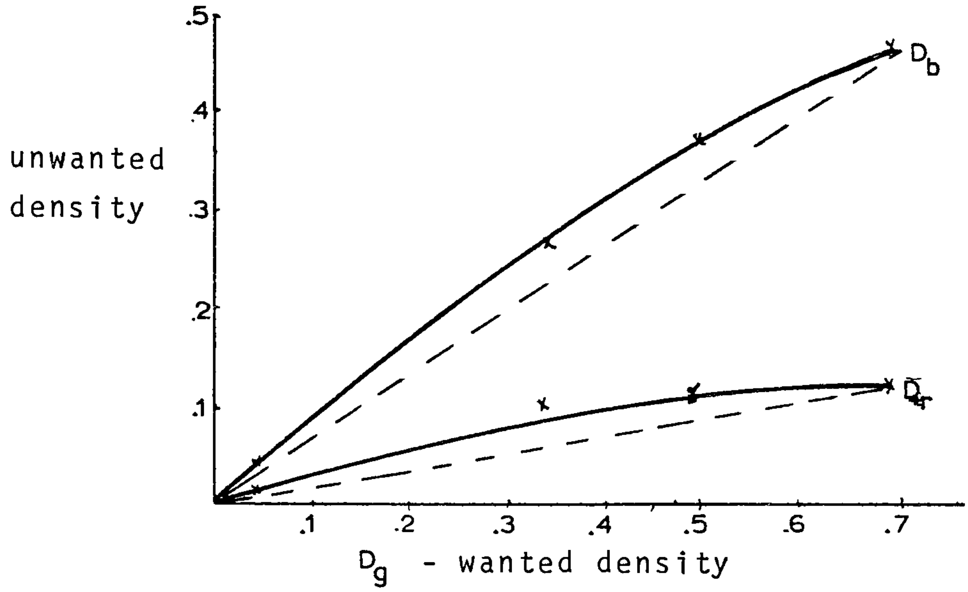

Figure A-10. Proportionality curve. Magenta - SID 0.65 - newsprint - 65 lines/inch.

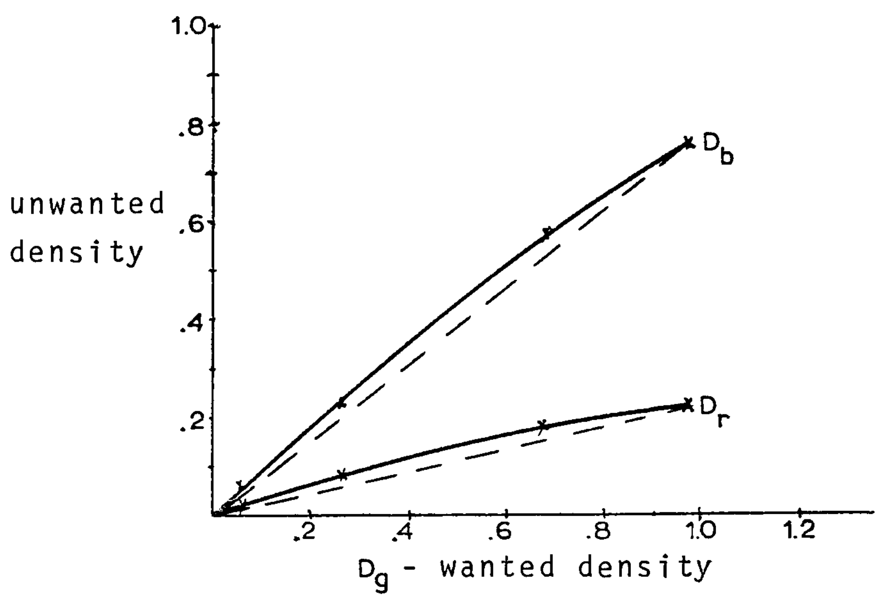

Figure A-11. Proportionality curve. Magenta - SID 0.97 - uncoated - 65 lines/inch.

APPENDIX A

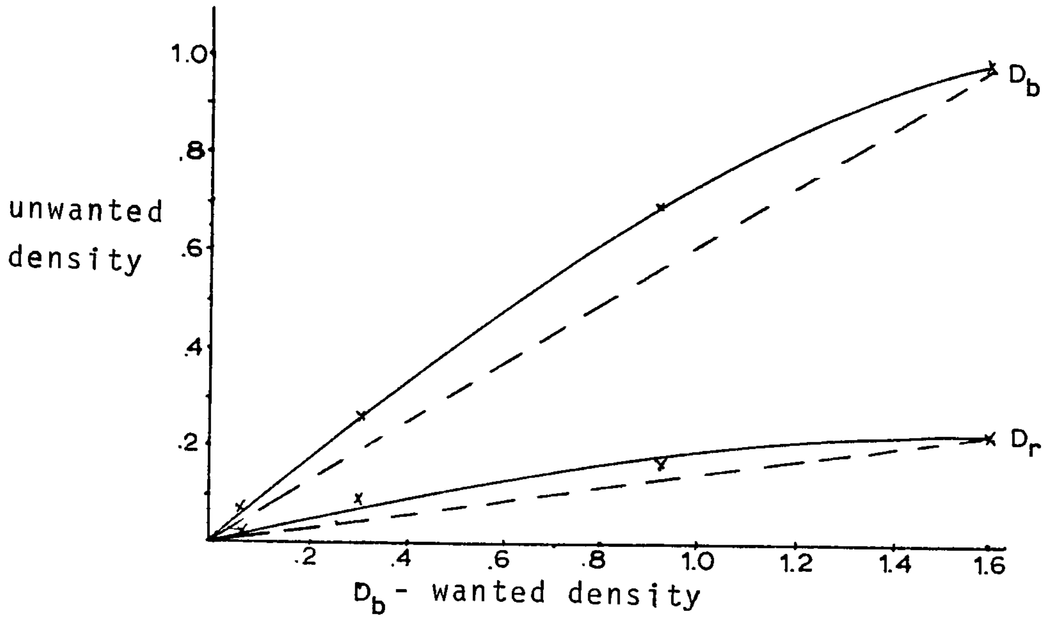

Figure A-12. Proportionality curve. Magenta - SID 1.60 - coated - 65 lines/inch.

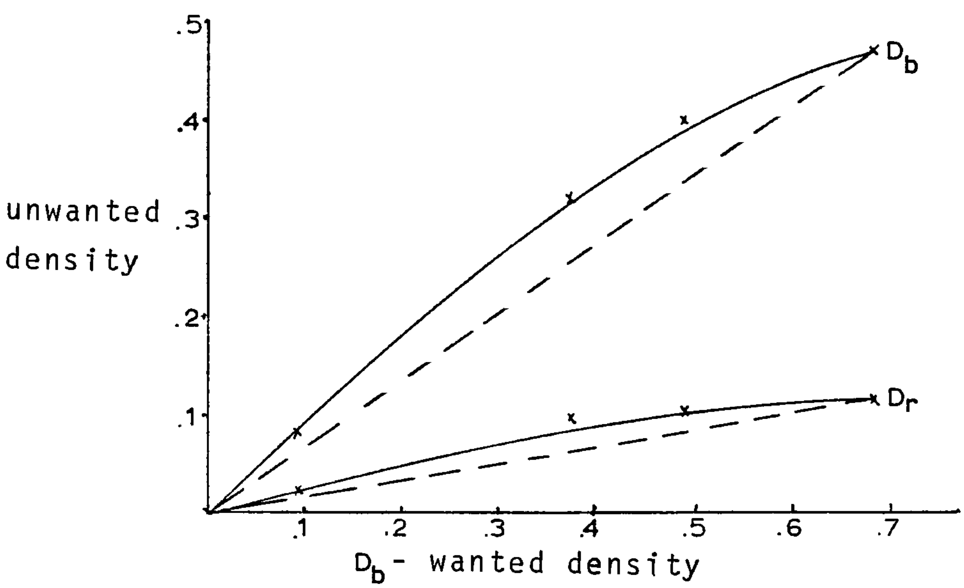

Figure A-13. Proportionality curve. Magenta - SID 0.65 - newsprint - 100 lines/inch.

APPENDIX A

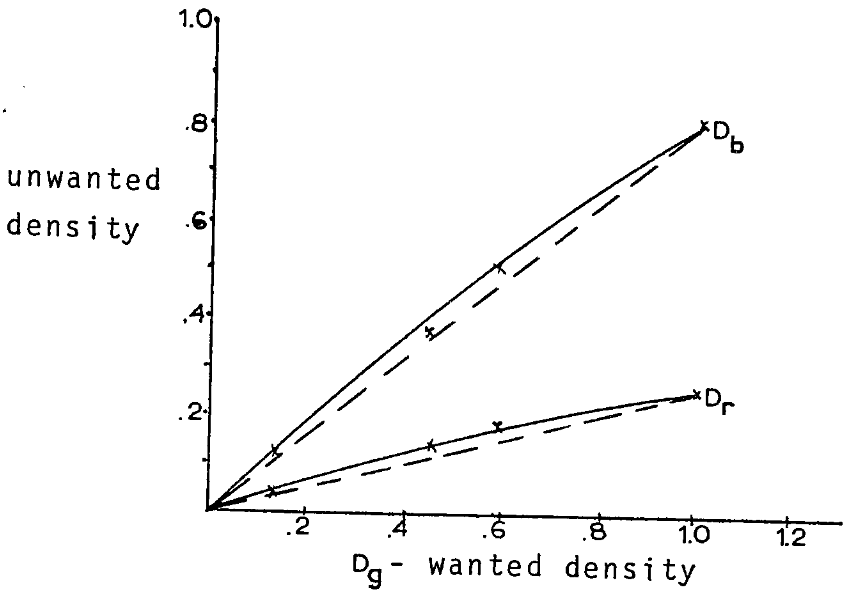

Figure A-14. Proportionality curve. Magenta - SID 0.97 - uncoated - 100 lines/inch.

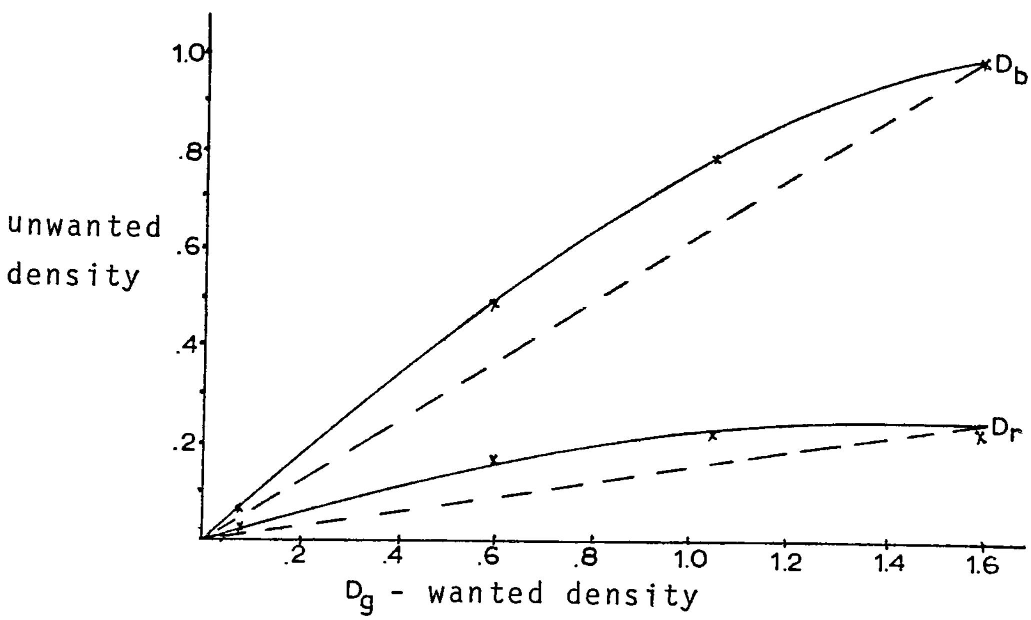

Figure A-15. Proportionality curve. Magenta - SID 1.60 - coated - 100 lines/inch.

APPENDIX A

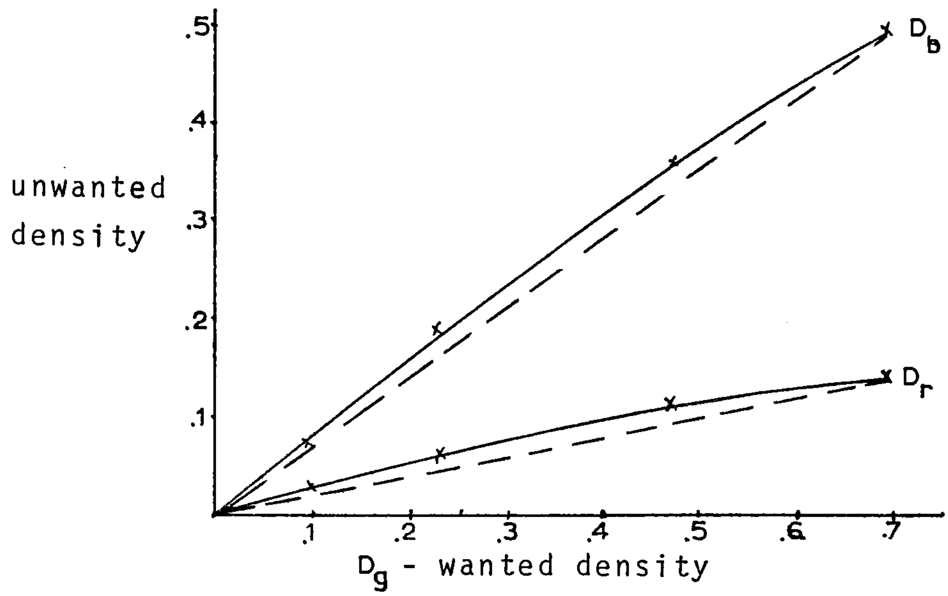

Figure A-16. Proportionality curve. Magenta - SID 0.65 - newsprint - 150 lines/inch.

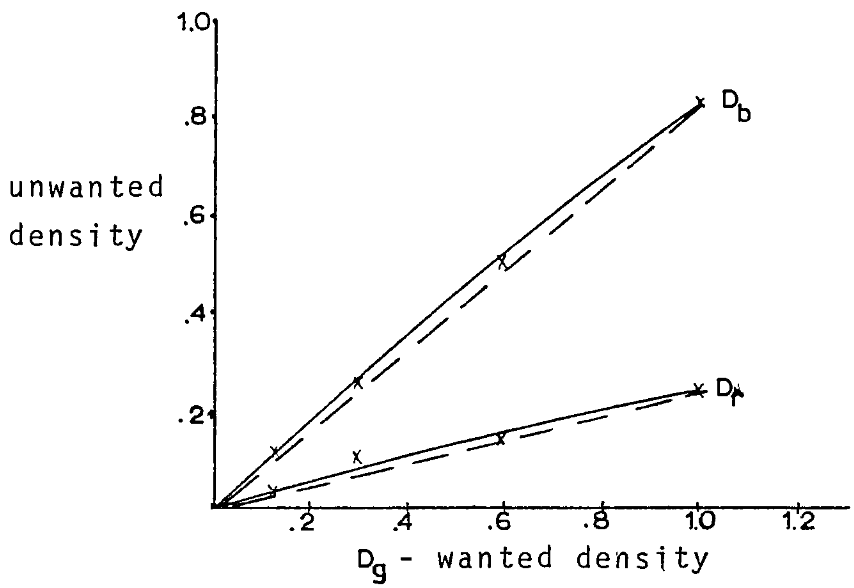

Figure A-17. Proportionality curve. Magenta - SID 0.97 - uncoated - 150 lines/inch.

APPENDIX A

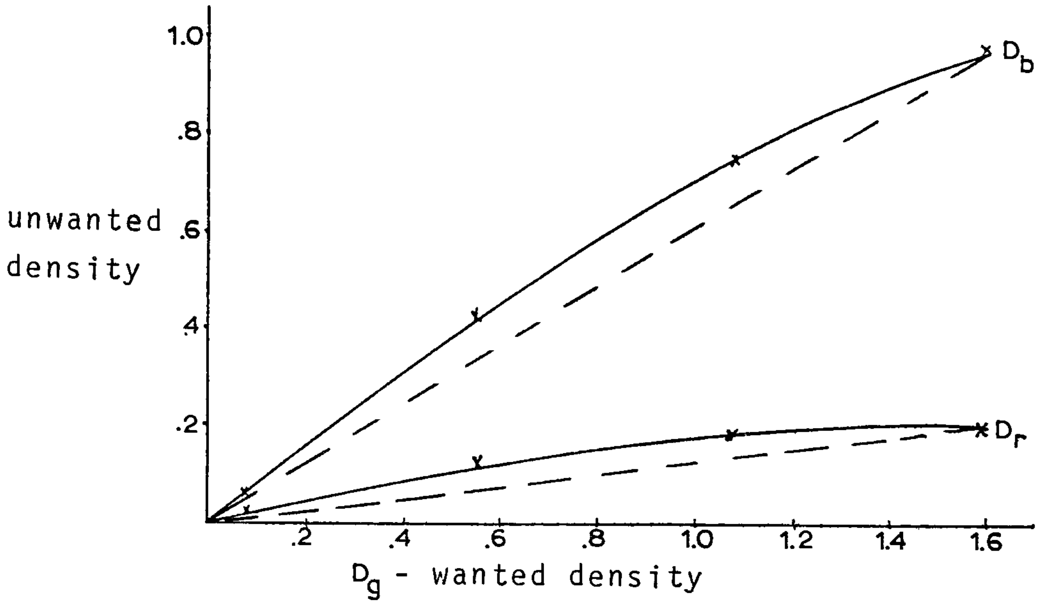

Figure A-18. Proportionality curve. Magenta - SID 1.60 - coated - 150 lines/inch.

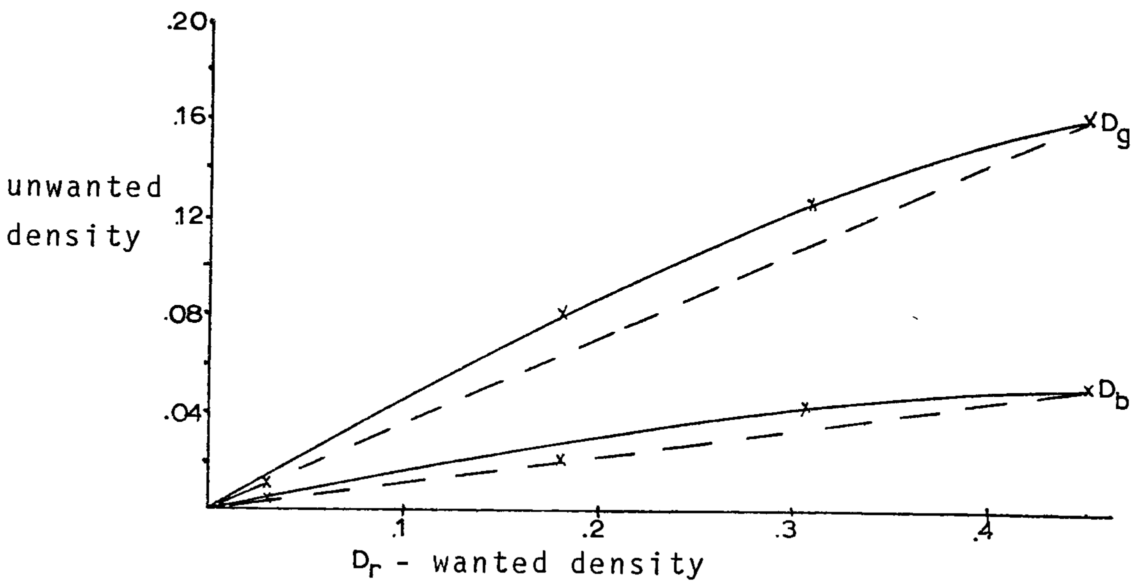

Figure A-19. Proportionality curve. Cyan - SID 0.45 - newsprint - 65 lines/inch.

APPENDIX A

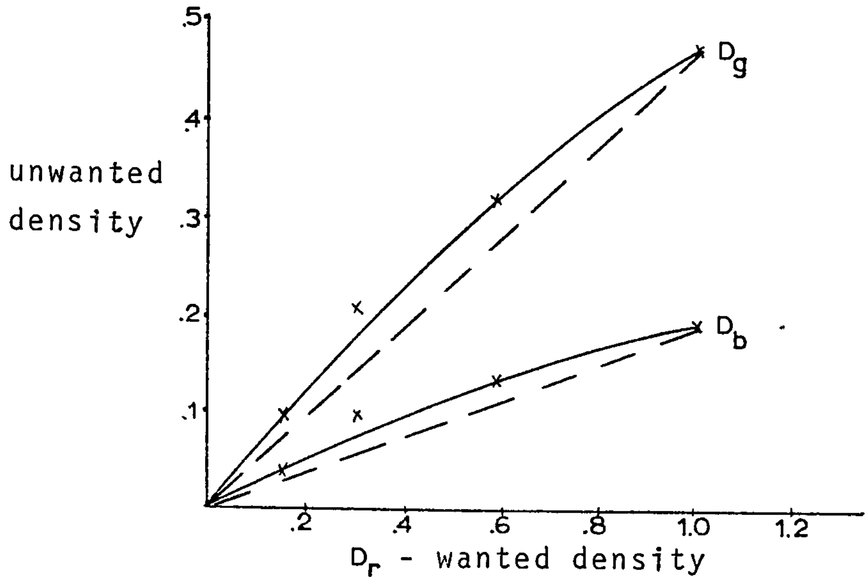

Figure A-20. Proportionality curve. Cyan - SID 1.00 - uncoated - 65 lines/inch.

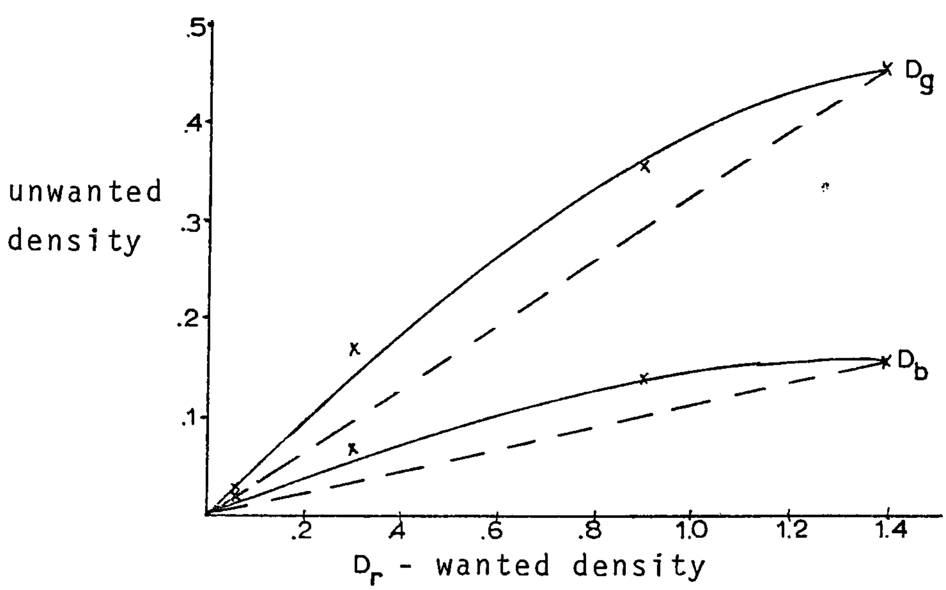

Figure A-21. Proportionality curve. Cyan - SID 1.42 - coated - 65 lines/inch.

APPENDIX A

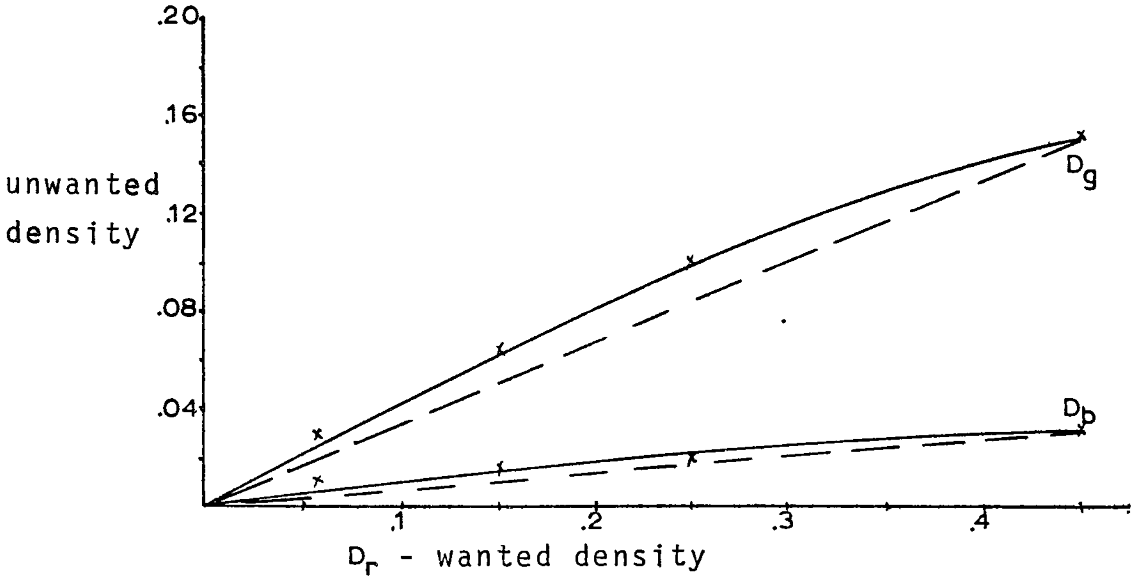

Figure A-22. Proportionality curve. Cyan - SID 0.45 - newsprint - 100 lines/inch.

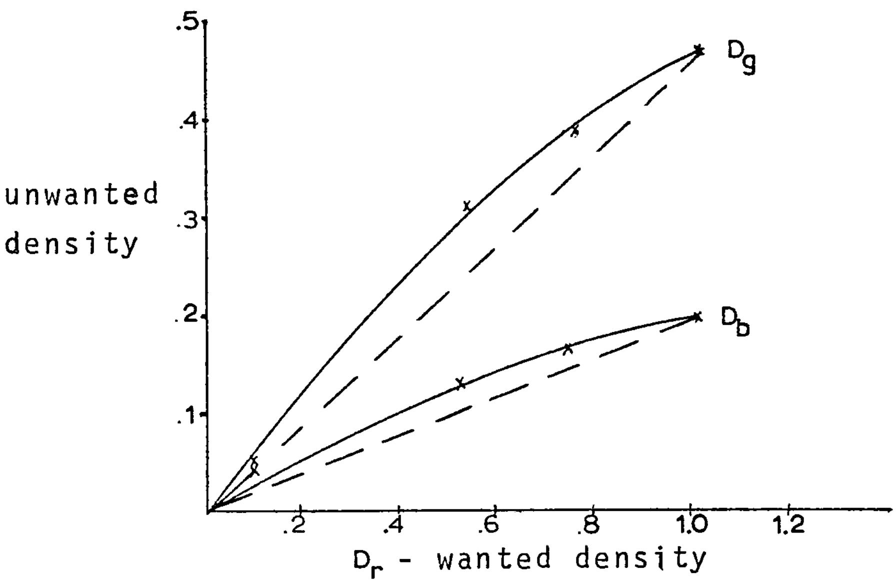

Figure A-23. Proportionality curve. Cyan - SID 1.00 - uncoated - 100 lines/inch.

APPENDIX A

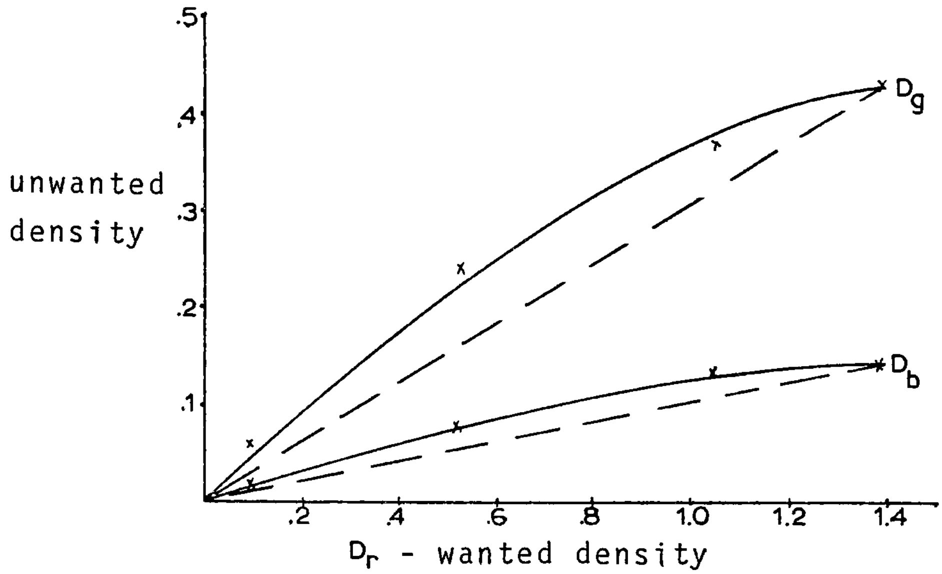

Figure A-24. Proportionality curve. Cyan - SID 1.42 - coated - 100 lines/inch.

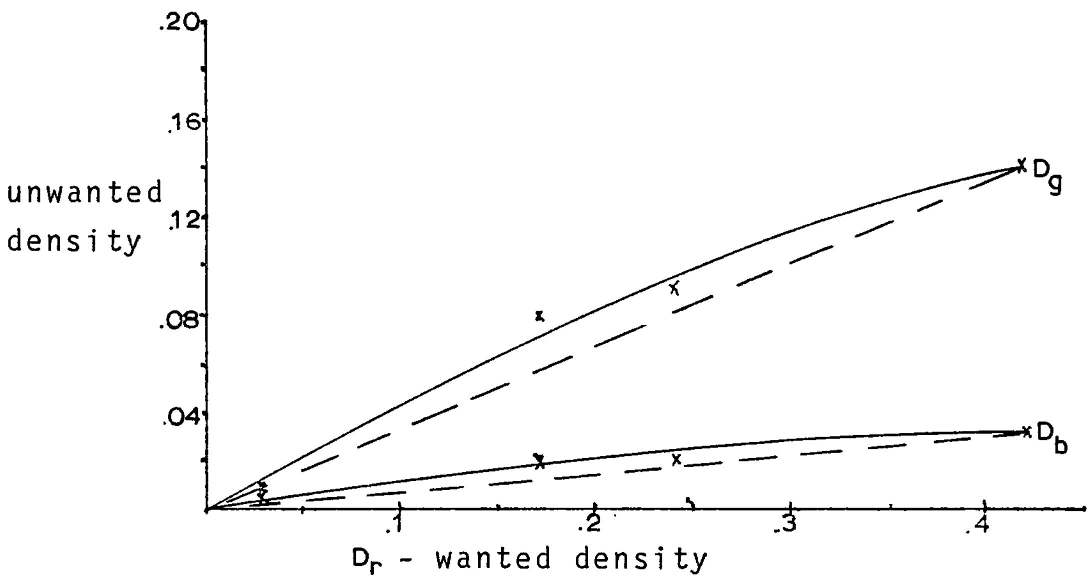

Figure A-25. Proportionality curve. Cyan - SID 0.45 - newsprint - 150 lines/inch.

APPENDIX A

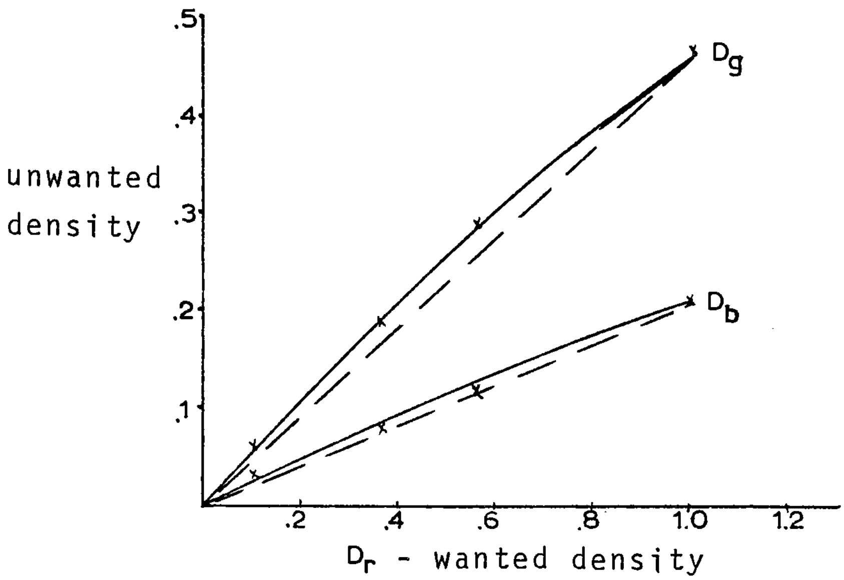

Figure A-26. Proportionality curve. Cyan - SID 1.00 - uncoated - 150 lines/inch.

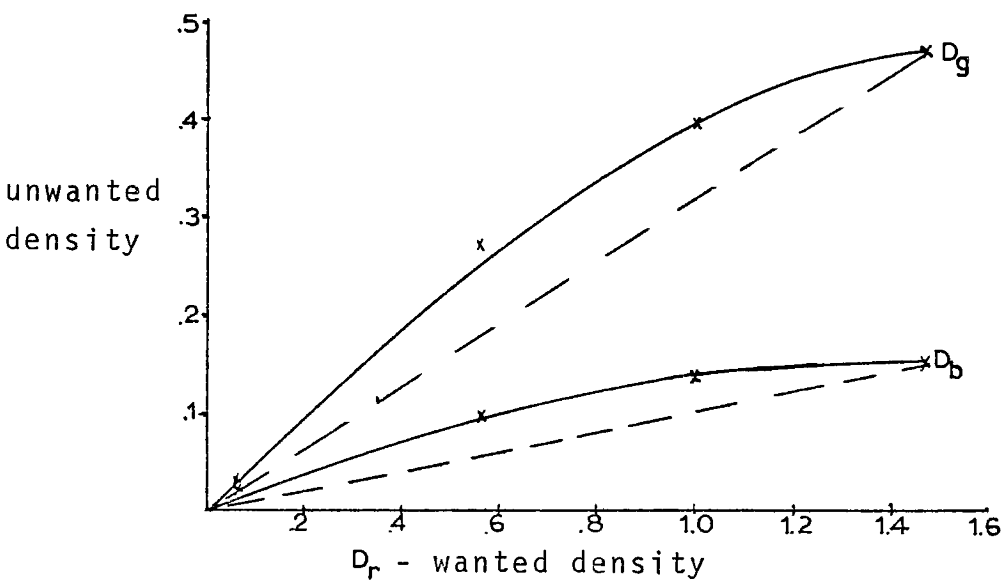

Figure A-27. Proportionality curve. Cyan - SID 1.42 - coated - 150 lines/inch.

APPENDIX B

On the following pages are the curves which indicate the relative amounts of proportionality failure caused by the screen ruling. The graphs are the ratio of unwanted-to-wanted densities (D_u/D_w) versus screen ruling. In these curves D_r, D_g, and D_b are the reflection densities with the red, green, and blue filters, respectively. In each case the curve of the solid reference (100% tint) was a straight horizontal line since the same solid ink density on the same type of paper will produce the same unwanted-to-wanted density ratio. Any deviation from the horizontal reference line indicates the proportionality failure which is being influenced by the change in screen ruling. The standard deviations (s) of the slopes of all the straight-line curves is noted on each graph. The average standard deviation ($\bar{S}$) from the two unwanted reflection densities is also noted and this is compared to the average proportionality failure index ($\bar{P}_f$) which was found by taking the average of the proportionality index readings from the paper and ink samples indicated over the range of screen-rulings used.

APPENDIX B

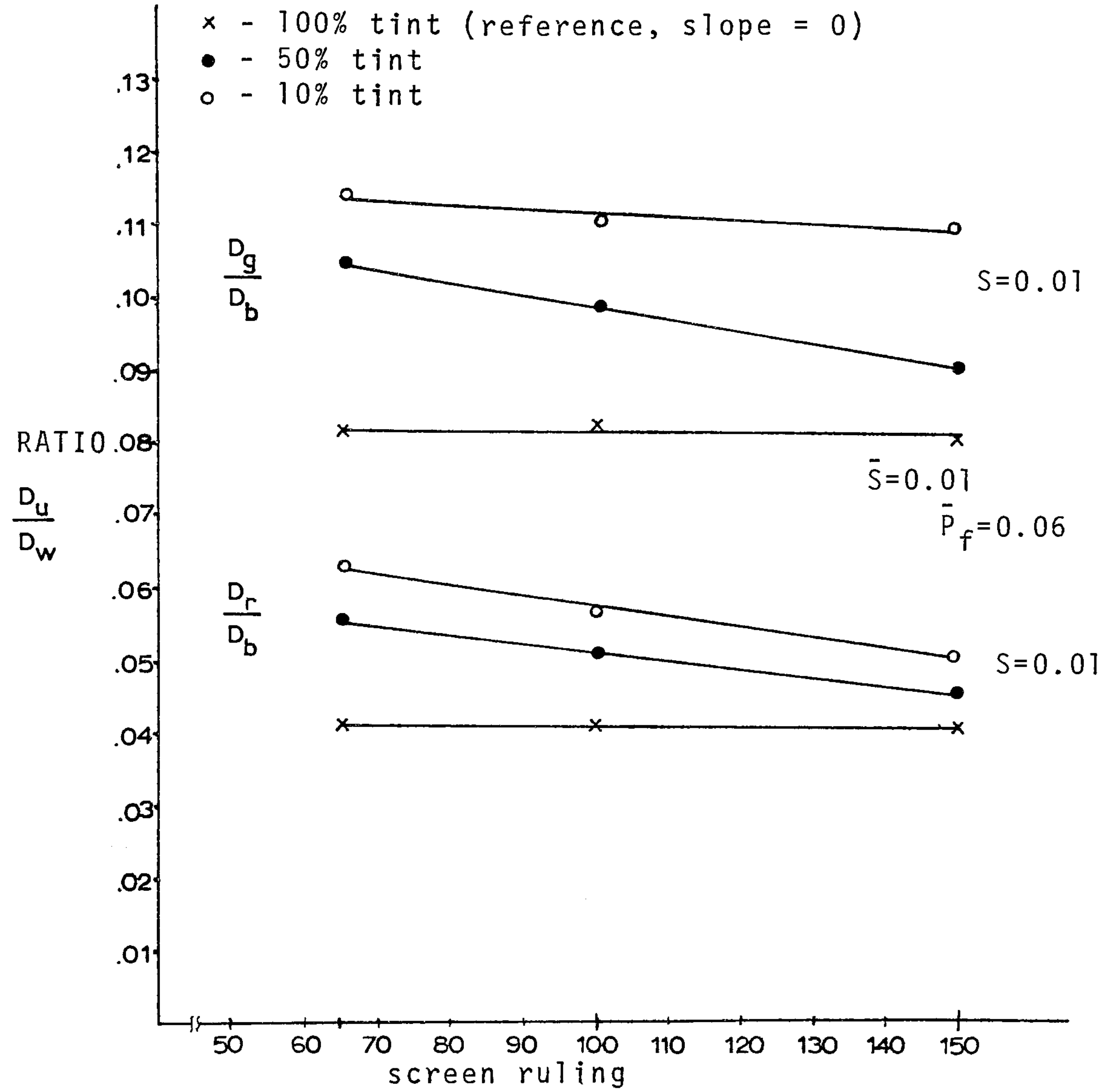

Figure B-1. Density ratios vs. Screen Ruling.
Yellow - SID 0.62 - newsprint.

APPENDIX B

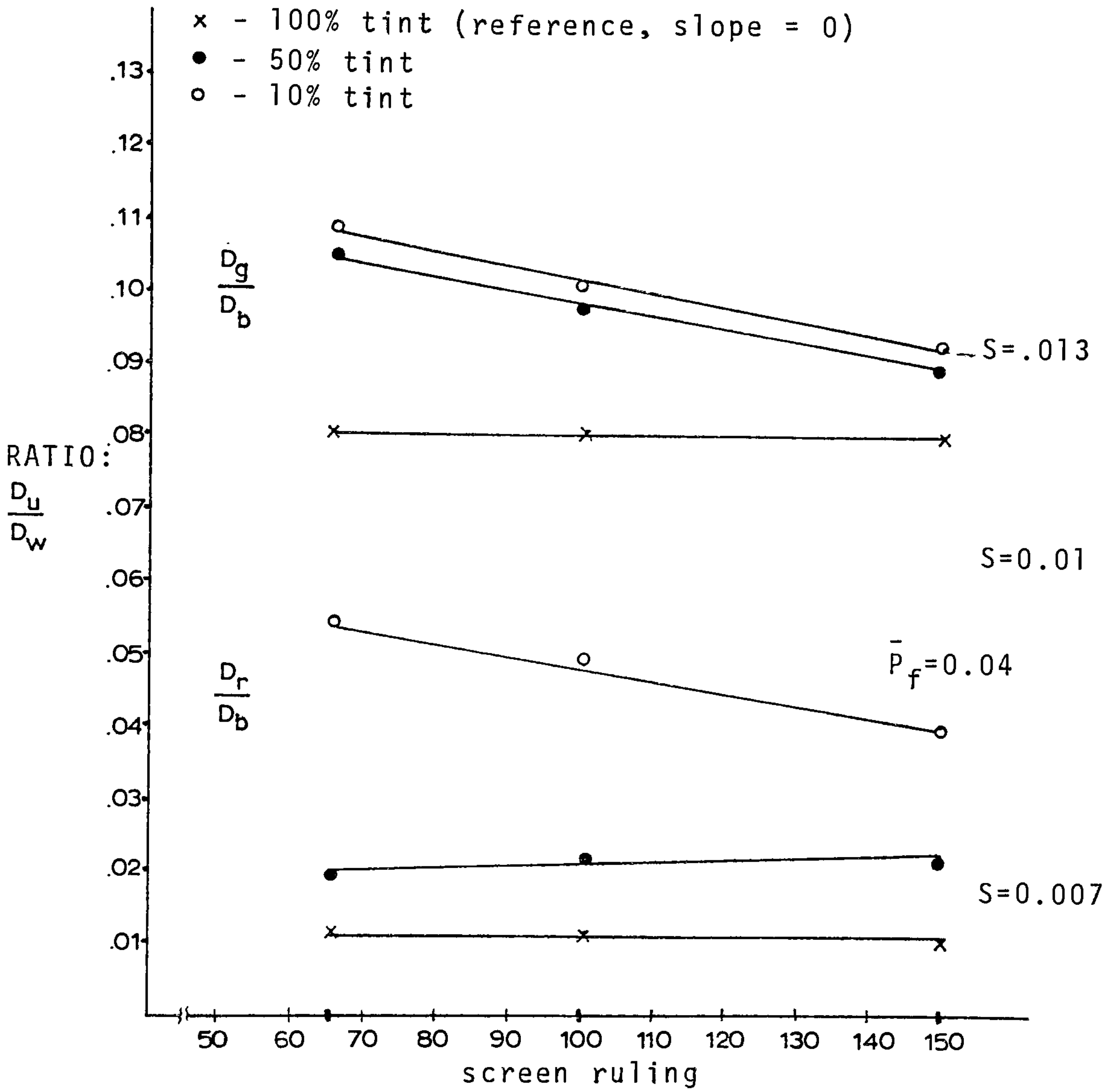

Figure B-2. Density ratios vs. Screen Ruling.
Yellow - SID 0.83 - uncoated.

APPENDIX B

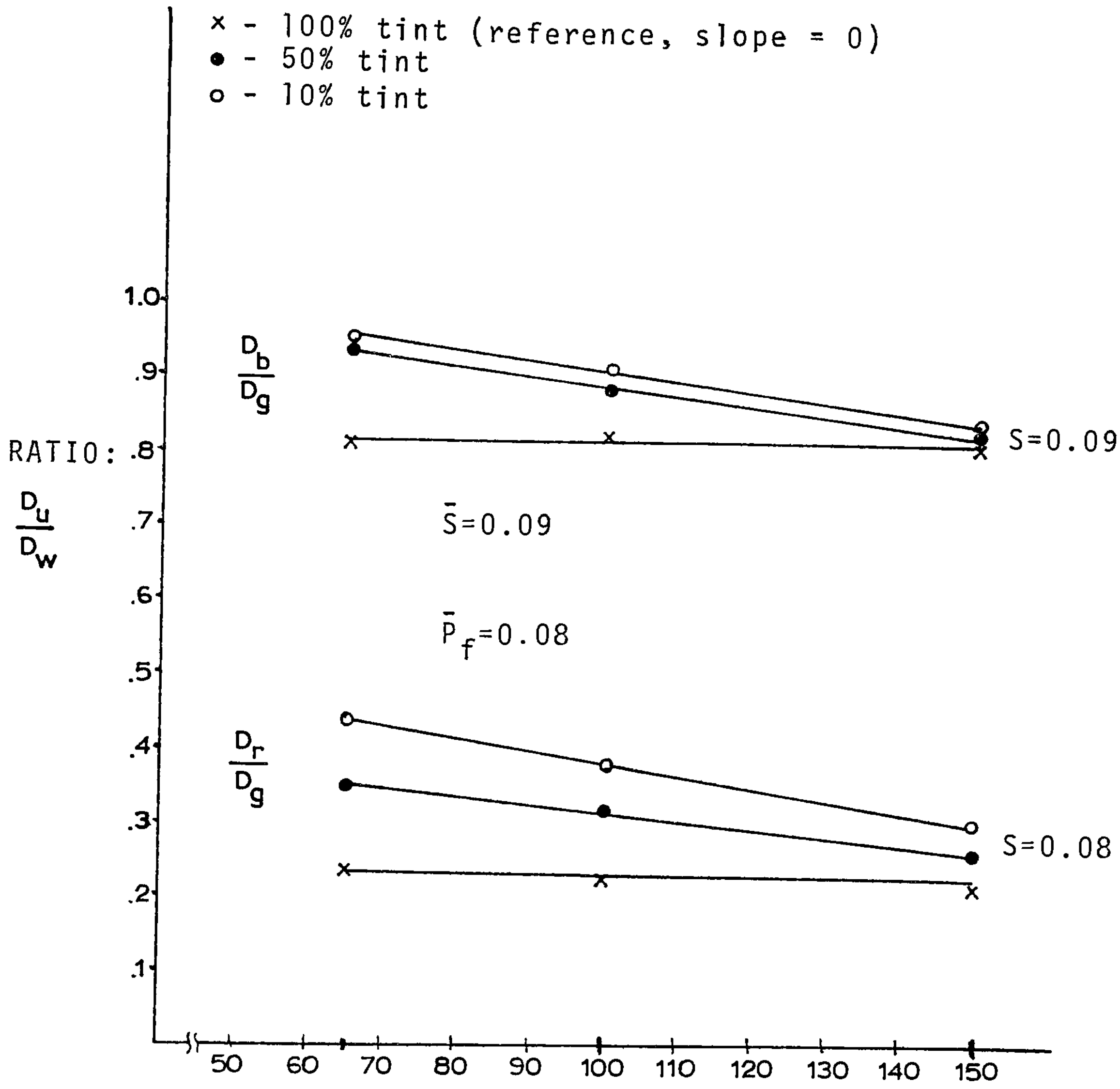

Figure B-3. Density ratios vs. Screen Ruling.
Magenta - SID 0.63 - uncoated

APPENDIX B

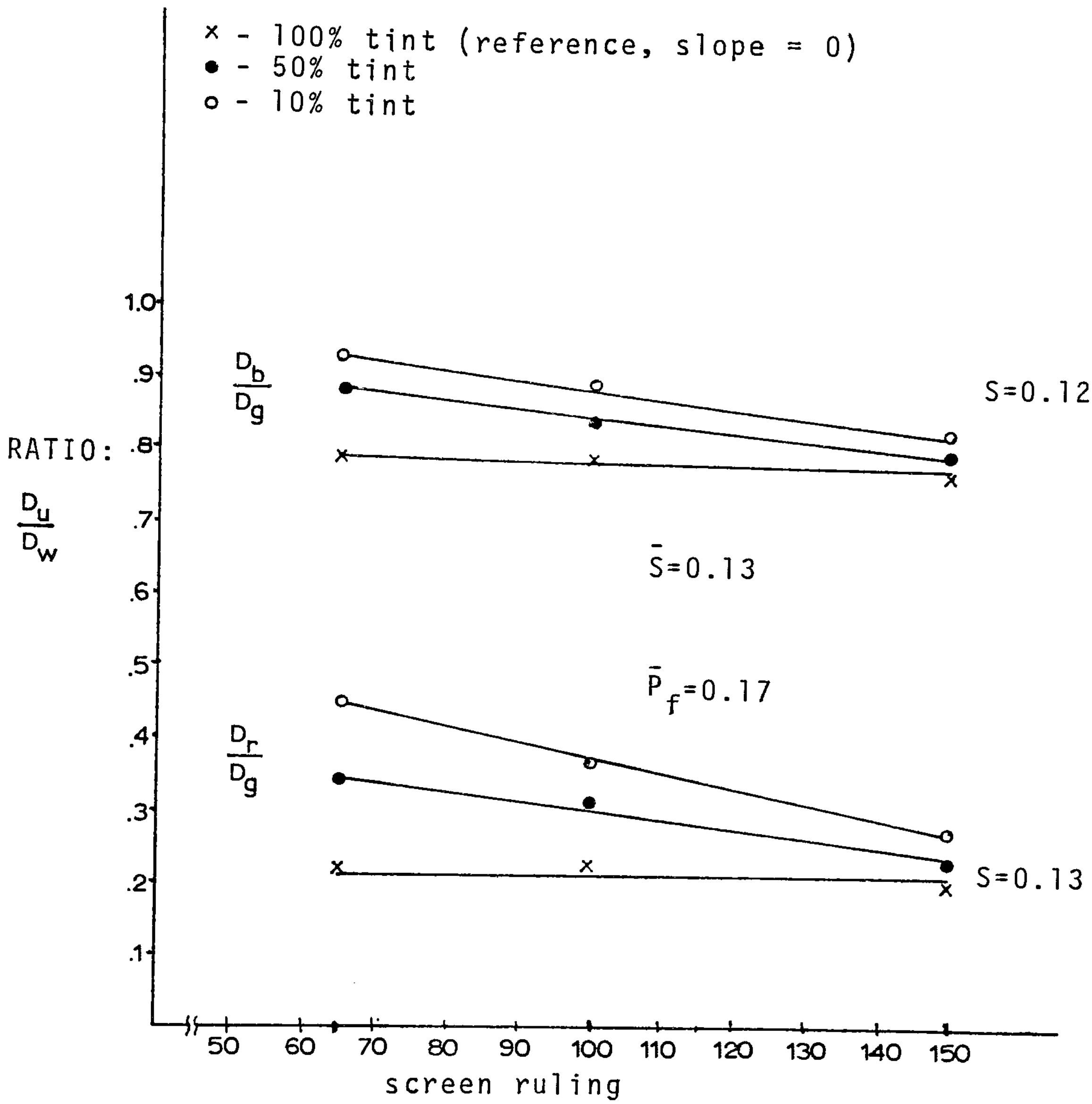

Figure B-4. Density ratios vs. Screen Ruling. Magenta - SID 1.10 - newsprint.

APPENDIX B

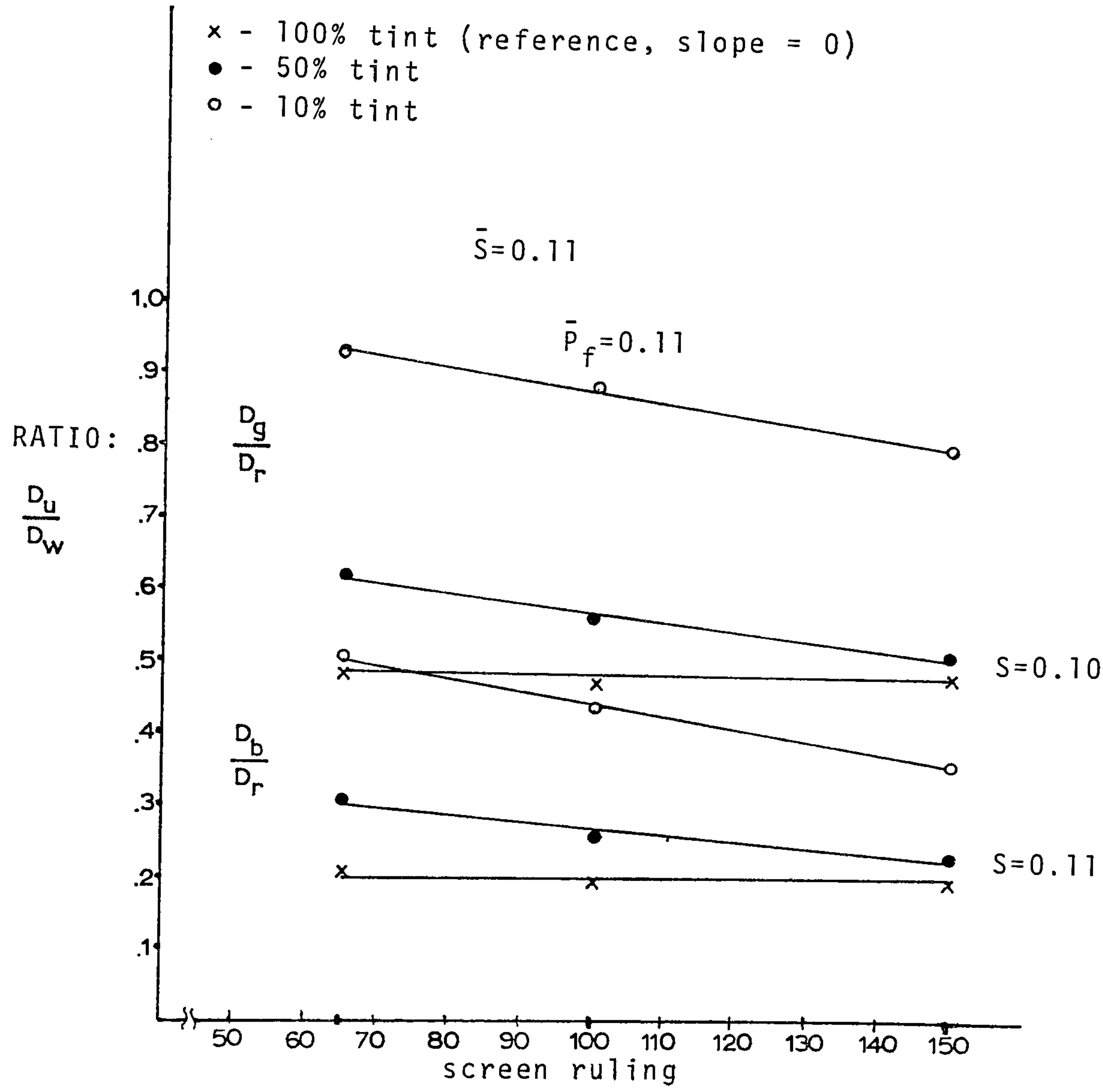

Figure B-5. Density ratios vs. Screen Ruling.
Cyan - SID 0.63 - uncoated.

APPENDIX B

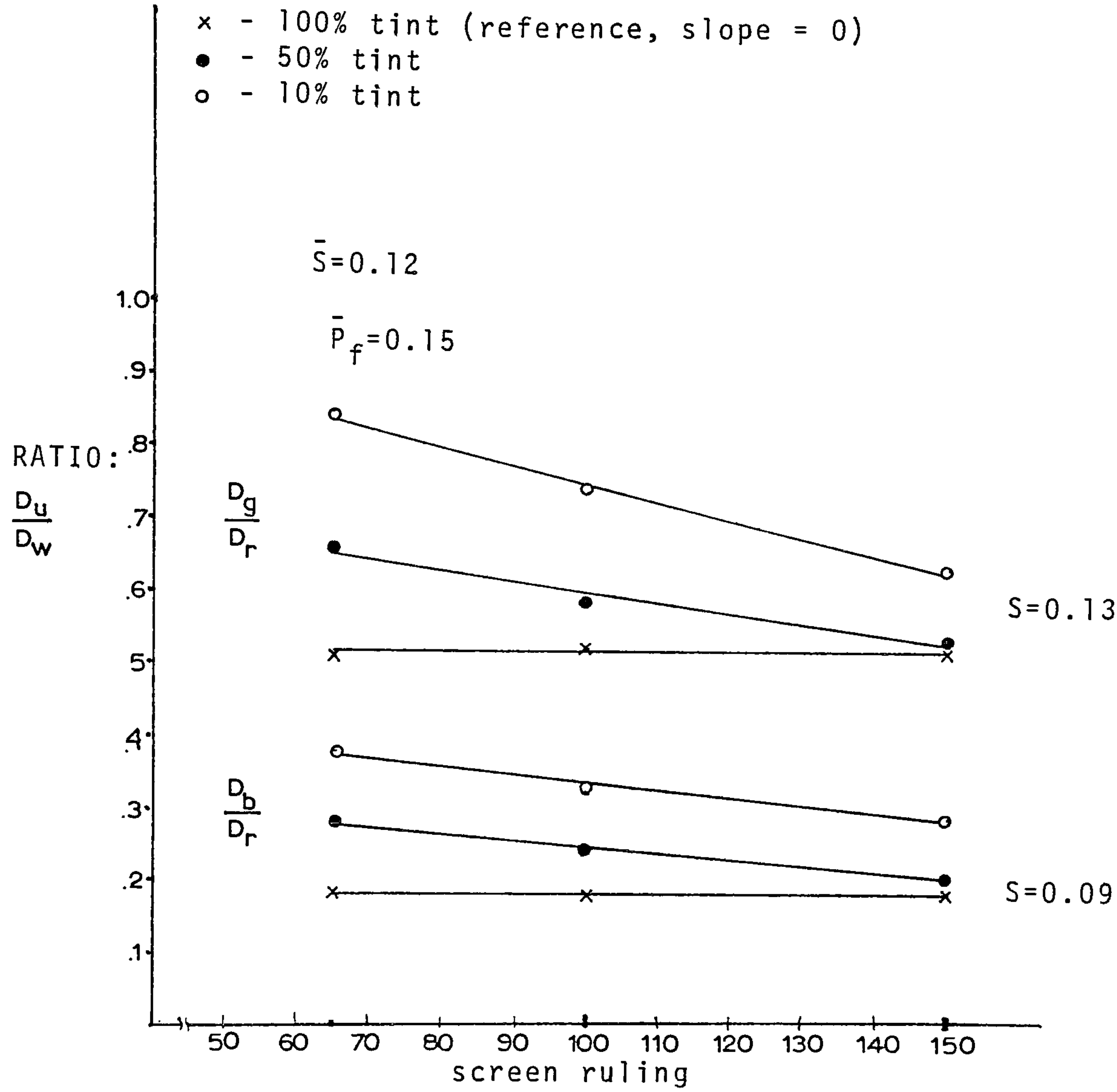

Figure B-6. Density ratios vs. Screen Ruling.
Cyan - SID 1.15 - newsprint.

APPENDIX C

On the following pages are the curves which indicate the relative amount of proportionality failure caused by variations in solid ink density. The graphs are the ratio of unwanted-to-wanted densities (D_u/D_w) versus the solid ink density. The interpretation of these graphs is the same as in Appendix B, with the standard deviations (S) of the sloped lines, which represent the plots for the 50% and 10% tints, to the reference lines (which aren't necessarily horizontal lines) being indicative of the relative amount of proportionality failure caused by variable solid ink density. The average standard deviations ($\bar{S}$) from the two unwanted reflection densities is noted and is compared to the average proportionality failure index ($\bar{P}_f$) which was found by taking the average of the proportionality failure index readings from the paper, ink, and screen ruling samples indicated over the range of solid ink density used. In these curves D_r, D_g, and D_b are the reflection densities with the red, green, and blue filters, respectively.

APPENDIX C

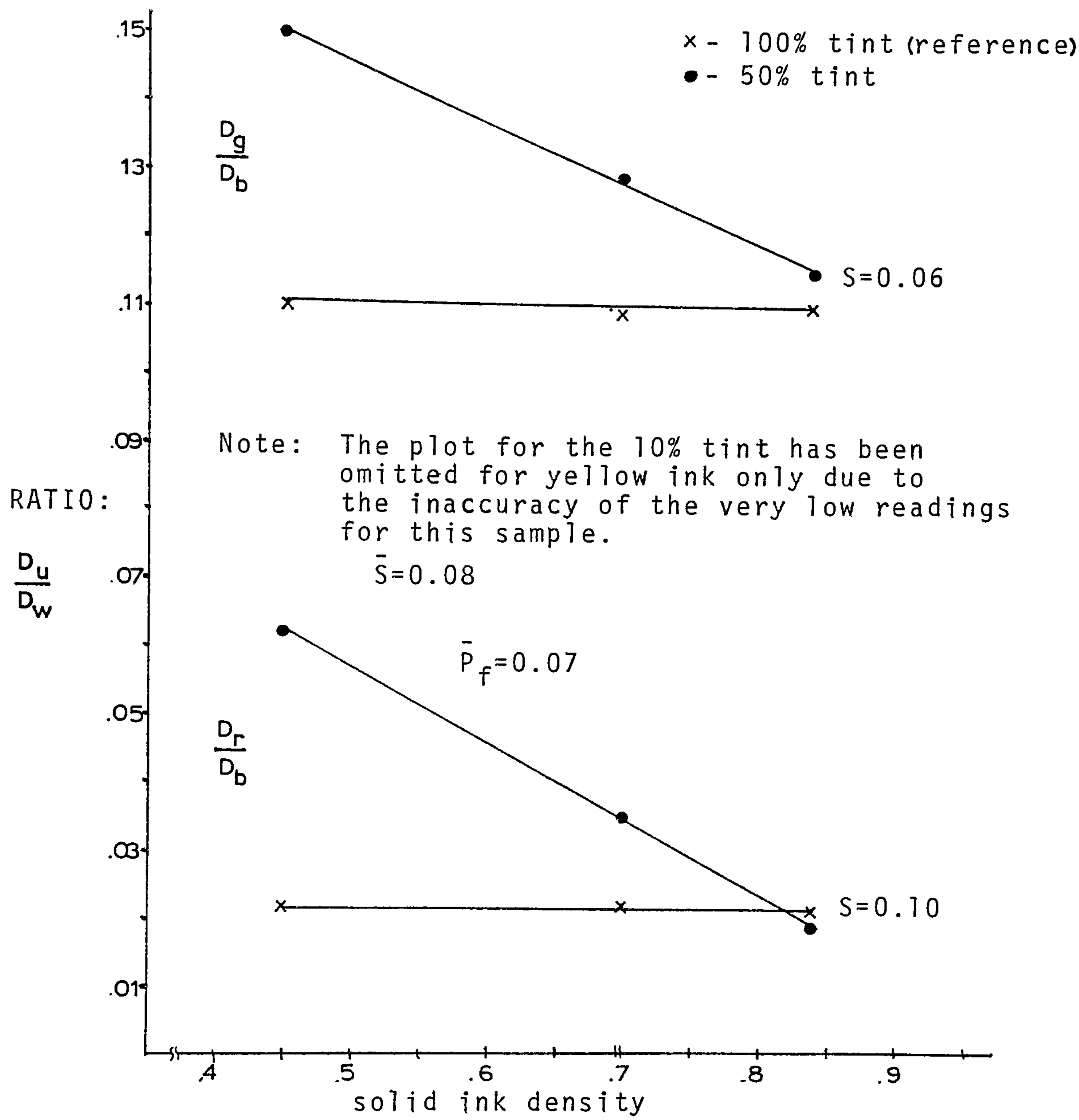

Figure C-1. Density ratios vs. SID. Yellow - newsprint - 65 lines/inch.

APPENDIX C

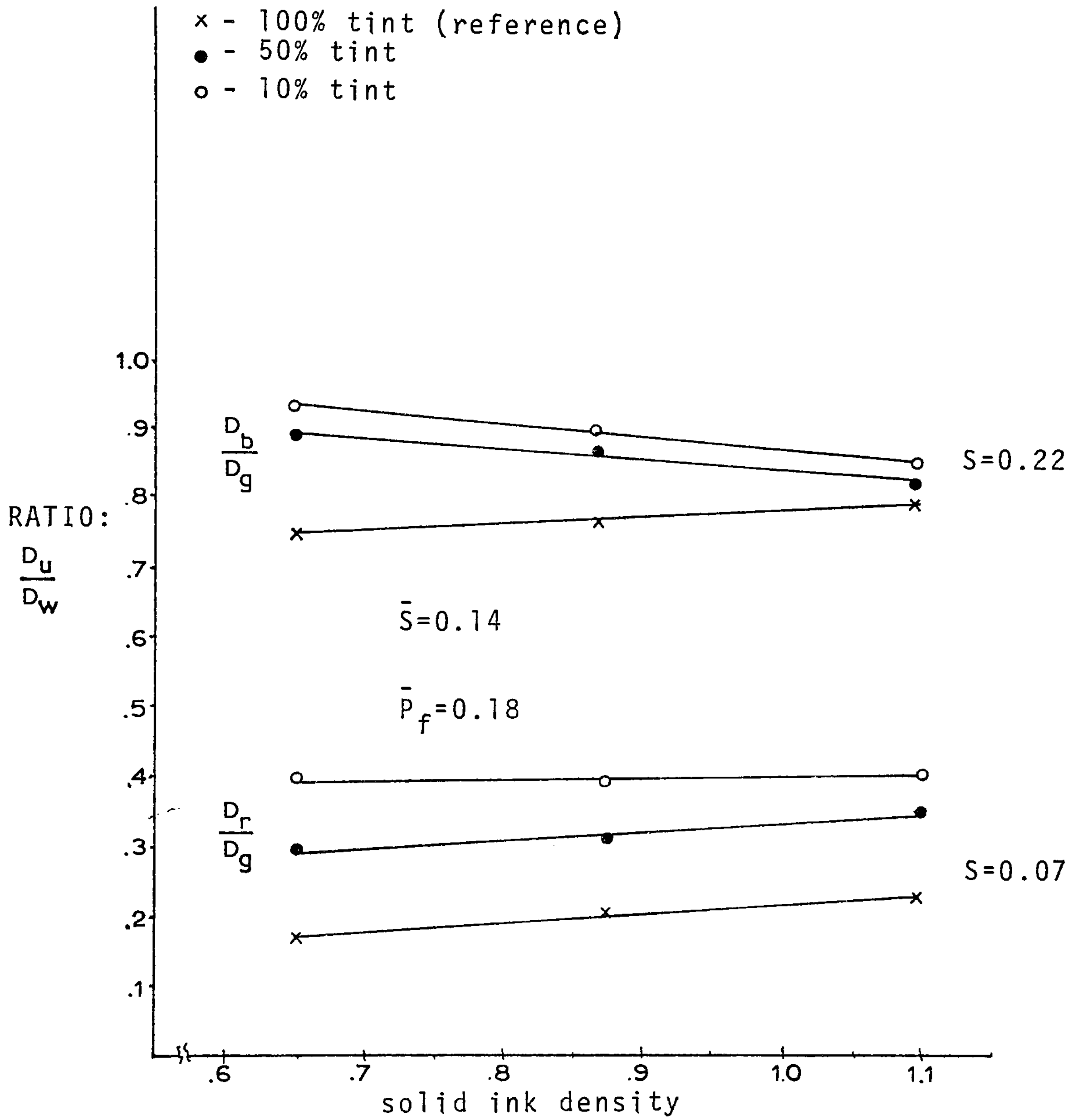

Figure C-2. Density ratios vs. SID. Magenta - newsprint - 65 lines/inch.

APPENDIX C

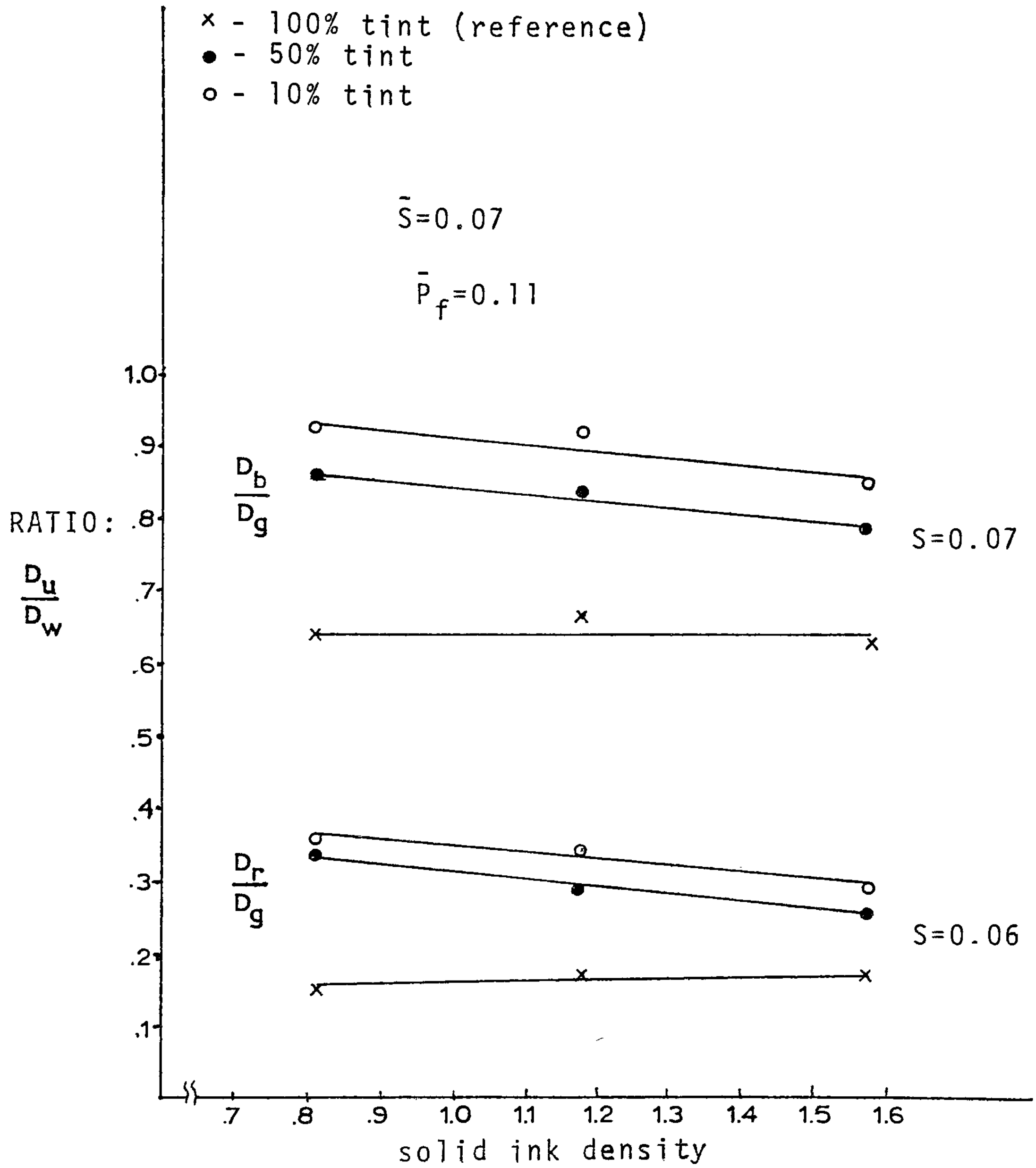

Figure C-3. Density ratios vs. SID. Magenta - coated - 150 lines/inch.

APPENDIX C

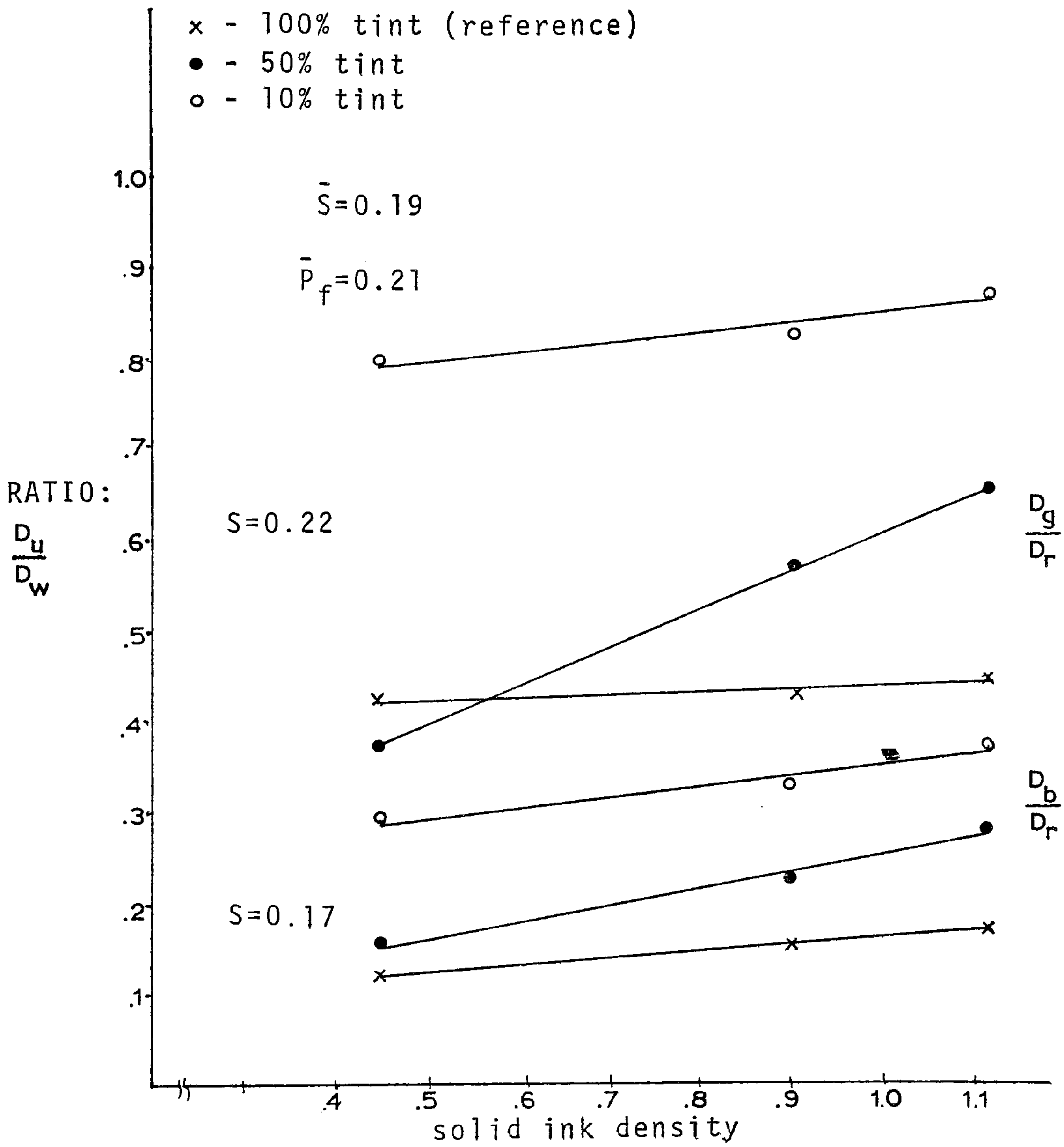

Figure C-4. Density ratios vs. SID. Cyan - newsprint - 65 lines/inch.

APPENDIX C

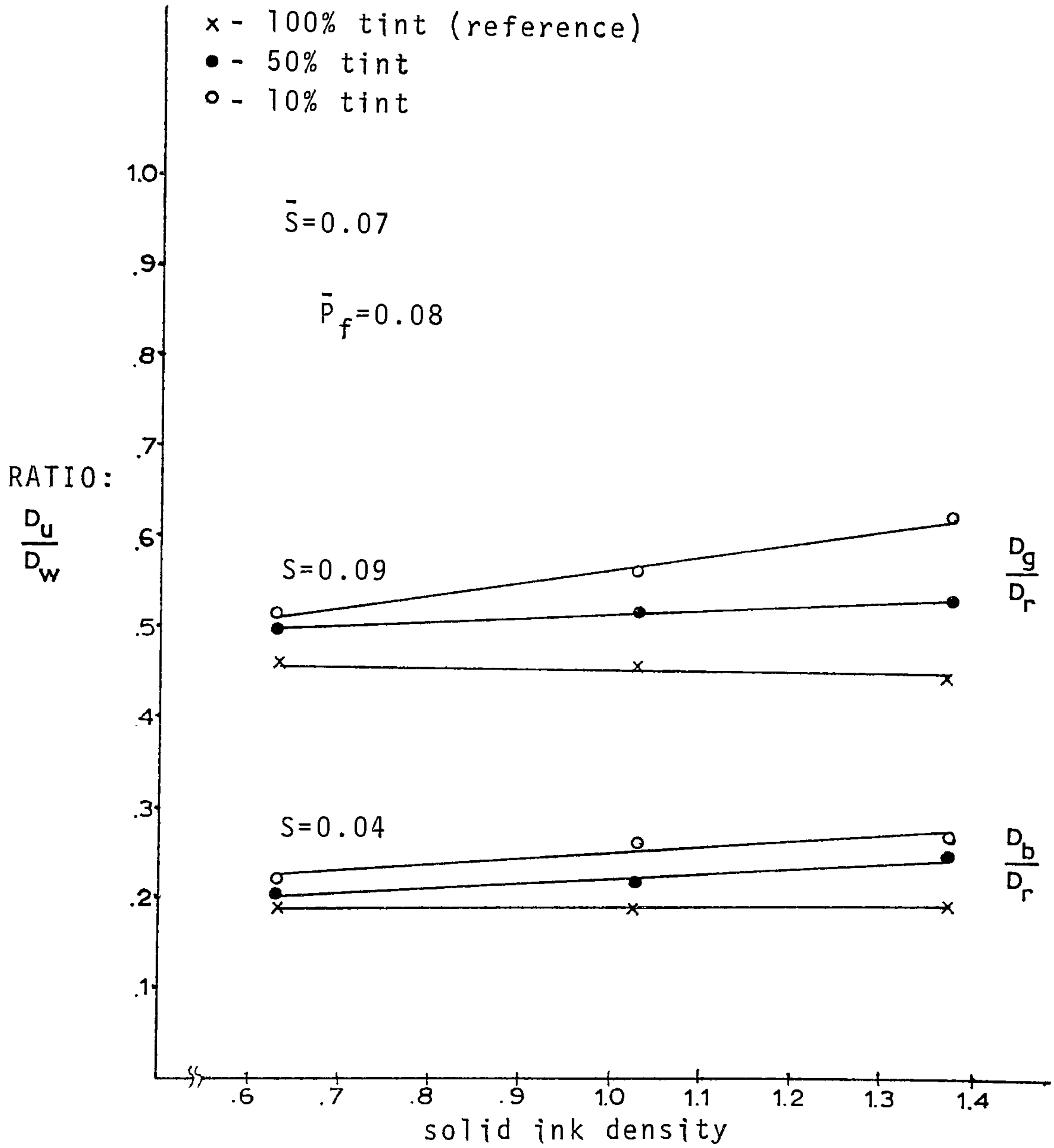

Figure C-5. Density ratios vs. SID. Cyan - uncoated - 150 lines/inch.